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# Radon-222 Emissions and Control Practices for Licensed Uranium Mills and Their Associated Tailings Piles

PEI Associates, Inc., Arlington, VA

Prepared for

Office of Radiation Programs, Washington, DC

Jun 85

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# RADON-222 EMISSIONS AND CONTROL PRACTICES FOR LICENSED URANIUM MILLS AND THEIR ASSOCIATED TAILINGS PILES

## FINAL REPORT

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The report is organized into five main sections. The conclusions of this effort are summarized in Chapter 2. A general description of current milling and tailings managment practices and a summary of the site-specific characteristics of operating and standby uranium mills are contained in Chapter-3. The sources and emission rates of radon-222 at licensed mills and their associated tailings piles are contained in Chapter 4 along with the results of an effort to develop generic procedures to estimate radon-222 emissions for milling operations and tailings disposal. Control practices that are being or could be applied to the milling operation and tailings disposal areas and their estimated cost and effectiveness in reducing radon-222 emissions are presented in Chapter 5. The appendices contain detailed information on mill site data and emission estimates.

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## CONTENTS

Page

Figures iv
Tables vi

1. INTRODUCTION 1-1

2. CONCLUSIONS 2-1

References 2-5

3. CHARACTERISTICS OF URANIUM MILLING AND TAILINGS DISPOSAL 3-1

3.1 Introduction 3-1
3.2 General Characteristics of Milling and Tailings Disposal 3-4
3.2.1 Uranium Milling 3-4
3.2.2 Tailings Management 3-11
3.3 Site-Specific Characteristics 3-15
3.3.1 Colorado 3-17
3.3.2 New Mexico 3-23
3.3.3 South Dakota 3-34
3.3.4 Texas 3-36
3.3.5 Utah 3-41
3.3.6 Washington 3-47
3.3.7 Wyoming 3-51

References 3-67

4. RADON-222 EMISSIONS FROM LICENSED MILLS AND TAILINGS PILES 4-1

4.1 Description of Radon-222 Sources 4-1
4.2 Estimation of Radon-222 Emissions 4-8
4.3 Application to Specific Facilities 4-15

References 4-18

5. CONTROL PRACTICES AND COST 5-1

5.1 Introduction 5-1
5.2 Control Practices for Active Tailings Areas 5-2
5.2.1 Earth Covers 5-2
5.2.2 Water Cover 5-9
5.2.3 Other Control Techniques 5-10

References 5-13

Appendix A - ESTIMATED POPULATIONS NEAR OPERATIONAL URANIUM ORE PROCESSING SITES

Appendix B - TECHNICAL INFORMATION MEMORANDUM ON RADON-222 EMISSIONS FROM OPERATIONAL URANIUM MILL FACILITIES

## FIGURES

| Number | | Page |
|---|---|---|
| 1-1 | Approximate locations of licensed conventional uranium mills | 1-3 |
| 3-1 | Simplified flow diagram of the acid leach process | 3-8 |
| 3-2 | Simplified flow diagram of the alkaline leach-caustic precipitation process | 3-10 |
| 3-3 | Embankment construction using coarse tailings | 3-14 |
| 3-4 | Location of mills in Colorado | 3-18 |
| 3-5 | Orientation of the cotter tailings piles and mill site | 3-20 |
| 3-6 | Location of mills in New Mexico | 3-24 |
| 3-7 | Configuration of the tailings pile at Sohio's L-Bar mill, and a cross-section through the dam | 3-25 |
| 3-8 | Diagram of the Homestake mill site and adjacent residential area | 3-31 |
| 3-9 | Location of the Edgemont mill | 3-35 |
| 3-10 | Location of mills in Texas | 3-37 |
| 3-11 | Diagram of Chevron's Panna Maria mill site and a cross-section through the tailings dam | 3-38 |
| 3-12 | Location of mills in Utah | 3-42 |
| 3-13 | Configuration of the tailings pile at the Moab mill | 3-44 |
| 3-14 | Location of mills in Washington | 3-48 |
| 3-15 | Diagram of the Dawn mill and associated tailings piles | 3-50 |
| 3-16 | Location of mills in Wyoming | 3-52 |
| 3-17 | Diagram of the Bear Creek mill site, tailings pile, and one of the mine pits | 3-57 |
| 3-18 | Orientation of the tailings pile and mill at Union Carbide's Gas Hills mill | 3-61 |
| 4-1 | Schematic illustration of the radon-222 sources at a uranium mill | 4-2 |

FIGURES (continued)

Number | | Page
---|---|---
4-2 | Time sequence of gaseous storage and release from the active uranium mill | 4-6
5-1 | Effect of soil thickness on radon-222 exhalation rate (Ro81) | 5-5

# TABLES

| Number | | Page |
|---|---|---|
| 3-1 | Status of operations and tailings disposal piles at licensed conventional uranium mills | 3-2 |
| 3-2 | Summary of the current status of uranium mill tailings piles | 3-13 |
| 4-1 | Previous estimates of radon-222 releases from operational uranium mills | 4-9 |
| 4-2 | Estimated radon emission rates for major radon-222 sources at operational mills in each uranium milling state | 4-11 |
| 4-3 | Estimates of radon-222 currently released from tailings piles at licensed uranium mills | 4-13 |
| 5-1 | Estimated earthen cover thickness needed to reduce radon-222 emissions to 20 $pCi/m^2$-s | 5-4 |
| 5-2 | Summary of radon-222 flux measurements at Grand Junction over a two-year period | 5-6 |
| 5-3 | Unit costs for estimating soil cover costs | 5-7 |
| 5-4 | Cost of attenuating radon-222 flux as a function of thickness and type of soil coverings | 5-8 |

# Chapter 1: INTRODUCTION

The U.S. Environmental Protection Agency, under section 112 of the Clean Air Act, as amended, is considering the development of standards to control radon-222 emissions at licensed uranium mills. This intention was specified in an Advance Notice of Proposed Rulemaking (49 FR 43916, October 31, 1984). Currently, the radon-222 emitted from licensed uranium mills and their associated tailings piles are subject to a limit of less than 3 pCi/l in the ambient air at the property line. Standards issued under the Uranium Mill Tailings Radiation Control Act (UMTRCA) do not specifically limit radon-222 emissions from tailings piles until after the closure period, at which time radon-222 releases to the atmosphere cannot exceed an average of 20 pCi/m$^2$-s (48 FR 45947, October 7, 1983). During processing operations and prior to the end of the closure period, radiation doses from radon-222 emissions from these piles and impoundments are to be kept as low as reasonably achievable (ALARA) at each licensed site [40 CFR 192.32(a)(4)]. In addition, radon-222 emissions from uranium ore milling and tailings disposal are not included in either the Environmental Radiation Protection Standards for Nuclear Power Operations (40 CFR Part 190) or standards proposed under the Clean Air Act (50 FR 5190, February 6, 1985), which regulate emissions from DOE facilities that comprise the uranium fuel cycle, NRC licensees and non-DOE Federal facilities, and elemental phosphorus plants, respectively.

This study was conducted to support the Office of Radiation Programs' standards setting activities under the Clean Air Act for radon-222 from uranium mills and associated tailings piles during their license period. Five mills are currently operating at reduced throughput; 16 other mills are licensed but are not operating because of depressed market conditions. Five additional mills have closed permanently and are either beginning or continuing decommissioning activities. An estimated 160 x $10^6$ t[*] of tailings are currently stored in piles covering about 3500 acres at these sites, which are located in Colorado, New Mexico, Washington, Utah, Wyoming, and Texas. The approximate locations of these mills are shown in Figure 1-1.

Uranium ore and mill tailings contain radium-226, which decays to radon-222 (a noble gas), a portion of which is emitted to the atmosphere. Radon-222 and its radioactive decay products may be inhaled, thereby increasing the risk of lung cancer to exposed individuals. Because the radioactive half-life of thorium-230, the precursor of radium-226, is 80,000 years, the potential radiation hazard posed by radon-222 from uranium mill tailings piles will last for thousands of years.

Milling consists of crushing, blending, and grinding steps, followed by leaching. Uranium is leached from the ore by an acid, alkaline, or combination process. The uranium is concentrated from the leach solution through ion exchange or solvent extraction. The concentrated uranium is then stripped or extracted from the concentrating medium, precipitated,

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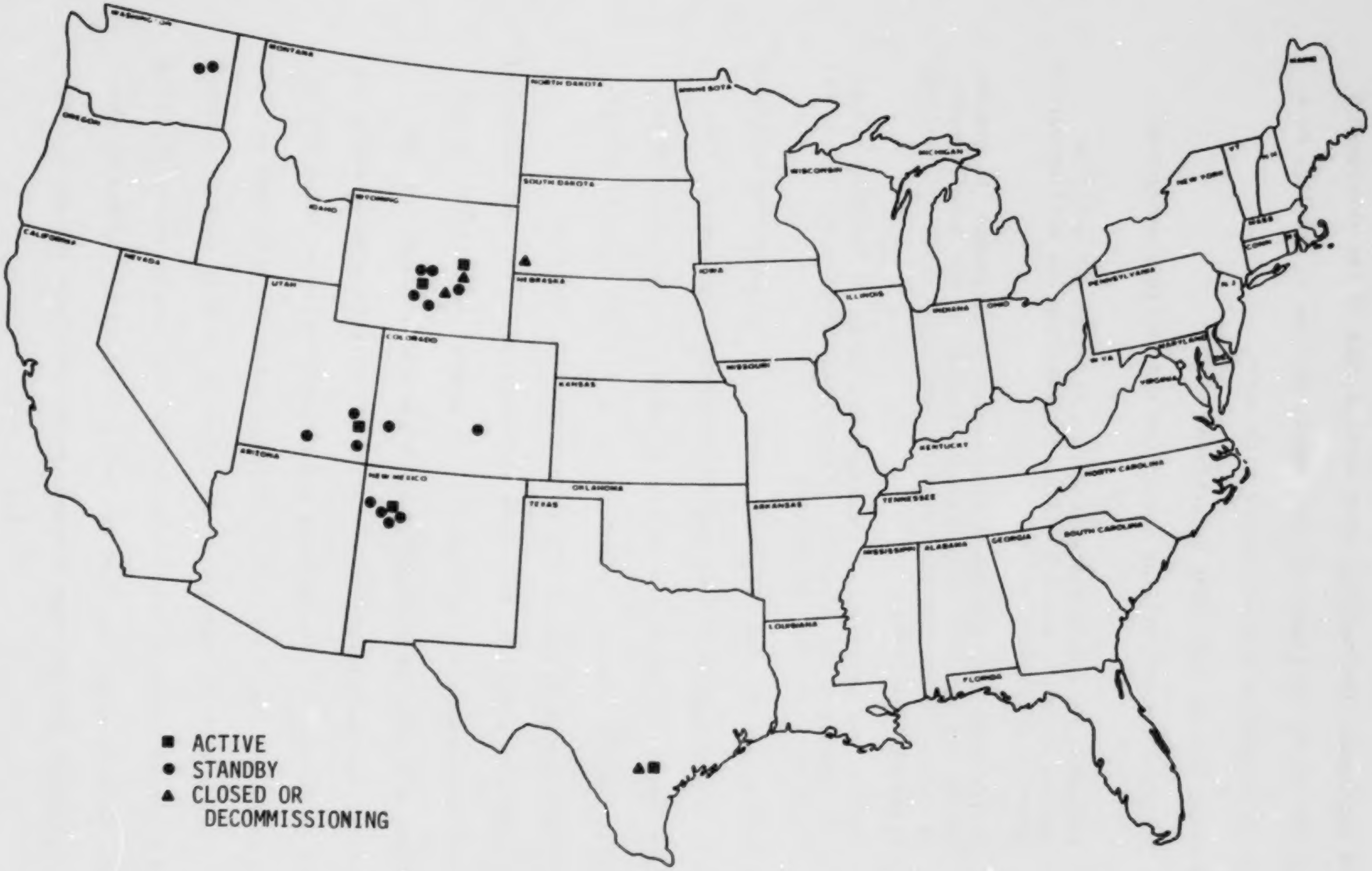
[*] t = metric ton.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▲ CLOSED OR DECOMMISSIONING
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MAINE

Figure 1-1. Approximate locations of licensed conventional uranium mills.

dried, and packaged. The tailings that contain most of the thorium-230 and radium-226 in the original ore are pumped, or flow by gravity, to a tailings pile or pond as a slurry mixed with water.

This study has the following objectives:

- Describe current milling operations and tailings management practices.
- Estimate, on a unit basis, the rate at which radon-222 is emitted from ore storage piles, ore handling and milling operations, and tailings piles.
- Review pertinent published information to determine the availability and accuracy of previous estimates of the total amount of radon-222 emitted from specific uranium milling and tailings disposal facilities.
- Discuss the efficiency of current practices in reducing radon-222 emissions and describe potential alternative practices that could control these emissions.

The information in this report is based on a review of the published literature; discussions with EPA, Nuclear Regulatory Commission (NRC), and State personnel; site visits to two operating uranium mills (Homestake Mining Company and Kerr-McGee/Quivira in New Mexico); and conversations with representatives of the uranium milling industry.

The report is organized into five main sections. The conclusions of this effort are summarized in Chapter 2. A general description of current milling and tailings management practices and a summary of the site-specific characteristics of operating and standby uranium mills are contained in Chapter 3. The sources and emission rates of radon-222 at licensed mills and their associated tailings piles are contained in Chapter 4 along with the results of an effort to develop generic procedures to estimate radon-222 emissions for milling operations and tailings disposal. Control practices that are being or could be applied to the milling operation and tailings disposal areas and their estimated cost and effectiveness in reducing radon-222 emissions are presented in Chapter 5. The appendices contain detailed information on mill site data and emission estimates.

# Chapter 2: CONCLUSIONS

A review of pertinent literature and discussions with industry and regulatory personnel indicated two major conclusions: first, only a limited number of measurements have been made of radon-222 emissions (radon-222 flux) from licensed uranium milling and tailings disposal facilities; and second, virtually all estimates of radon-222 emissions from operational facilities have been based on these same few measurements. Very few of the uranium mill operators could provide actual measurements of radon-222 emanating from milling operations or tailings. None had made measurements of radon-222 emanating from the water-covered portion of active ponds. Measurements of ambient concentrations of radon-222 at the perimeter of all mill sites have been made because they are required by current regulations; however, the radon-222 measured at these locations is contributed by natural sources and uranium mine vents in addition to that from the mill and tailings pile. Operators generally report that the influence of the mill and tailings piles on ambient radon-222 concentrations cannot be detected at distances greater than 0.4 km (0.25 mi.) from these sources.

The NRC Final Generic Environmental Impact Statement (FGEIS) on Uranium Milling, published in 1980, is the reference cited for the majority of radon-222 estimates that have been made for licensed mills. The

NRC report assumed a radon-222 flux of 1.0 pCi radon-222/$m^2$-s per pCi radium-226/g tailings, a homogeneity of tailings characteristics, and if there is water cover, radon-222 emissions are prohibited (NRC80). These assumptions were based on previous research; however, measurements have not been made at enough active mill sites to fully evaluate their accuracy. In addition, insufficient site-specific data are available for most mill sites to apply these generic emission rates. Particularly, measurements of radium-226 concentrations in tailings and accurate measurements of the sizes of these piles are not available for most mills.

The uranium industry is currently depressed due to lack of demand and foreign competition. Only five uranium mills are operating (active status), and most of these mills are operating below their rated capacity. Sixteen mills are licensed but not operating (standby status) because of the depressed market. Five mills are licensed but have ceased operations and are either beginning or continuing decommissioning activities. Uranium mills typically are located in rural, sparsley populated areas. A 1983 population estimate indicated a total of 14,700 residents lived within 5 km (3.1 mi.) of these tailings piles, and 31 of these inhabitants lived within 0.5 km (0.3 mi.). No inhabitants lived within 5 km (3.1 mi.) at six sites (EPA83).

The tailings disposal area is the major source of radon-222 emanating from uranium mills. Approximately 160 x $10^6$ t of mill tailings are contained in tailings piles covering about 3800 acres (total) at these facilities. Each facility typically has one to four tailings piles. The majority of these piles have earthen embankments, usually constructed across natural drainages, to contain the tailings. Seven piles have coarse tailings as the embankment construction material. Only two piles have been constructed below grade.

The current source term of radon-222 emitted from tailings piles at licensed uranium mills is estimated to be 120 kCi/yr. This is based on the use of radon-222 flux of 1 pCi of radon-222/m$^2$ per pCi of radium-226/g of tailings, which is widely used and is the rate assumed in the NRC's FGEIS. The calculation was based on information presented in Chapter 3 on the current size of each tailings pile, radium-226 content of tailings at each site, and the area covered by tailings solution. Additionally, independent estimates of radon-222 emitted from coarse, dry tailings, wet fine (slime) tailings, and water-covered tailings were made in an effort to corroborate the generic rate that is typically used. This alternative calculation indicates that the current radon-222 source term from tailings piles at licensed uranium mills is 54 kCi/yr. Estimates were also made of radon-222 contributed by ore storage, handling, and milling to confirm that tailings piles are the major source of radon-222 at licensed mills.

No controls are currently used at licensed mills specifically to limit radon-222. Several aspects of current management practices act to limit radon-222 emanation, however. The embankments of most piles are constructed of earthen material and at least a portion of the tailings is covered by water or saturated. These factors limit the radon-222 emanating from the piles. In addition, the slimes (fine fraction of tailings that contains most of the radium-226) typically are contained in the center portion of the pile, which is the portion that is kept saturated or covered with water. Methods for reducing radon-222 emissions that might be applied to a licensed mill's tailings pile include partial earthen covers, increased water cover, or synthetic covers. These techniques can effectively reduce emissions, but must be considered on a site-specific basis since existing tailings disposal areas were not designed to include such control measures. Dike stability, construction equipment access to the tailings, and availability of cover material are key factors affecting the applicability of control measures.

About 1 to 3 meters of soil (depending largely on its moisture content) would be required to reduce radon-222 emissions to about 20 $pCi/m^2$-s. This cover material would cost from about \$50,000 to \$165,000 per acre of tailings. Estimates of the amount of cover required to reduce radon-222 and, therefore, the costs are subject to a high degree of uncertainty.

# REFERENCES

| | |
|---|---|
| EPA83 | U.S. Environmental Protection Agency, Office of Radiation Programs, Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192), EPA 520/1-83-008-1, September 1983. |
| NRC80 | Nuclear Regulatory Commission, Final Generic Environmental Impact Statement on Uranium Milling, NUREG-0706, September 1980. |

# Chapter 3: CHARACTERISTICS OF URANIUM MILLING AND TAILINGS DISPOSAL

## 3.1 Introduction

Only five conventional uranium mills are currently operating; 16 others are shut down and are on a standby status. These mills are listed in Table 3-1, together with their current status and nominal capacities. In 1983, the industry used only 33 percent of its capacity (DOE84). At that time, 12 conventional mills were operating. Due to the depressed market for uranium yellow cake, domestic production is expected to continue its decline over the next few years before starting a steady increase of 5 to 6 percent per year to the year 2000 (DOE84). Two of the mills that are currently on standby status might close permanently in the near future. The Petrotomics plant in Shirley Basin, Wyoming, is likely to close in 1985. The Uravan Mill of UMETCO (Union Carbide) was shut down in November 1984 for at least 2 years, and possibly permanently if a suitable new tailings disposal site cannot be found. Three mills that have been licensed but not yet constructed or have not become operational are not included in this evaluation.

This study was able to use site-specific information in developing radon-222 source terms because of the limited number of operational facilities. Thus, a model mill approach was not used. The site-specific information and data used in this study were obtained from reports

Table 3-1. Status of operations and tailings disposal piles at licensed conventional uranium mills(a)

| State | Facility | Owner | Operating status | Capacity (t/day) | Total tailings ($t \times 10^6$) | Total size (acres) |
|---|---|---|---|---|---|---|
| Colorado | Canon City | Cotter Corp. | Standby | 1200 | 0.9 | 140 |
| | Uravan | Union Carbide | Standby | 1300 | 8.9 | 80(b) |
| New Mexico | L-Bar | Kennecott | Standby | 1500 | 1.5 | 125 |
| | Churchrock | United Nuclear | Standby | 4000 | 3.1 | 50 |
| | Bluewater | Anaconda | Standby | 6000 | 25 | 208(c) |
| | Quivira | Kerr-McGee | Standby | 7000 | 25 | 328 |
| | Grants | Homestake | Active (anticipated standby July 1985) | 3400 | 19(d) | 210(d) |
| South Dakota | Edgemont | TVA | Decommissioning | -- | 2.6 | 168 |
| Texas | Panna Maria | Chevron | Active | 2500 | 1.4 | 140 |
| | Conquista | Conoco/Pioneer | Decommissioning | -- | 5.6 | 250 |
| | Felder | Exxon | Decommissioning | -- | 1.7(e) | 50(e) |
| Utah | White Mesa | Union Carbide | Standby | 2000 | 0.6 | 200 |
| | La Sal | Rio Algom | Active | 750 | 1.6 | 35 |
| | Moab | Atlas | Standby | 1400 | 7.0 | 125 |
| | Shootaring Canyon | Plateau Resources | Standby | 800 | NA | 70 |
| Washington | Ford | Dawn Mining | Standby | 600 | 2.0 | 139(f) |
| | Sherwood | Western Nuclear | Standby | 2000 | 1.5 | 135 |

(continued)

Table 3-1 (continued)

| State | Facility | Owner | Operating status | Capacity (t/day) | Total tailings (t x $10^6$) | Total size (acres) |
|---|---|---|---|---|---|---|
| Wyoming | Highland | Exxon | Decommissioning | 3200 | 7.0 | 200 |
| | Gas Hills | American Nuclear Corp | Decommissioning | 950 | 4.1 | 129[g] |
| | Sweetwater | Minerals Exploration | Standby | 3000 | 0.9 | 45 |
| | Gas Hills | Pathfinder | Standby | 2500 | 7.7 | 159 |
| | Shirley Basin | Pathfinder | Active | 1800 | 5.3 | 263 |
| | Shirley Basin | Petrotomics | Standby | 1500 | 2.8 | 140 |
| | Bear Creek | Rocky Mt. Energy | Active | 2000 | 2.7 | 120 |
| | Gas Hills | Union Carbide | Standby | 1400 | 7.6 | 186[h] |
| | Split Rock | Western Nuclear | Standby | 1700 | 11 | 125 |
| Total | | | 5 Active<br>16 Standby<br>5 Decommissioning | | 156.6 | 3820 |

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[a] Data obtained from NRC84 and updated by conversations with agreement states, NRC representatives, and mill operators. Does not include mills licensed but not constructed.

[b] Pile at capacity, stabilization and reclamation being initiated. If mill reopens, a new pile will be constructed (Kr85).

[c] Two smaller inactive piles (24 and 47 acres) of old tailings also are present and contain 1 x $10^6$ MT, included in totals (DOE82).

[d] One additional pile of tailings from earlier operations covers 40 acres and contains 1.2 x $10^6$ MT, included in total acreage (DOE82).

[e] From EPA83a.

[f] One 111-acre pile is at capacity, a 28-acre below-grade pit is being used for tailings disposal (An84).

[g] Includes 40 acres of inactive AEC tailings (DOE82)..

[h] One 160-acre pile is at capacity; a newer 26-acre pit is being used (Wo85).

published by the Nuclear Regulatory Commission (NRC), the U.S. Environmental Protection Agency (EPA), and from information supplied by NRC, state, and site personnel. In particular, the following reports were used: "Directory and Profile of Licensed Uranium Recovery Facilities" (NRC84), "Final Generic Environmental Impact Statement on Uranium Milling" (NRC80), "Regulatory Impact Analysis of Environmental Standards for Uranium Mill Tailings at Active Sites" (EPA83a), Department of Energy's Commingled Uranium Tailings Study (DOE82), and Final Environmental Statements for several mills. Data were updated and confirmed through conversations with representatives of agreement states (Colorado, New Mexico, Texas, and Washington) and personnel at the Uranium Field Office of NRC in Denver for mills in Wyoming and Utah. In addition, telephone conversations and written transmittals with mill operators were used to complete and confirm much of the data.

The purpose of the effort to compile site-specific information was to provide an accurate description of current milling operations and tailings management practices. This site-specific information serves as the basis for the estimation of radon-222 emissions. In the following discussion, a general description of uranium milling and tailings disposal is presented in order to identify points of radon-222 release. The details of each operational mill and tailings pile are presented in site-specific descriptions.

## 3.2 General Characteristics of Milling and Tailings Disposal

### 3.2.1 Uranium Milling

Milling is the process whereby uranium is extracted from the crude ore and concentrated to yield yellowcake--an intermediate, semirefined product. Conventional milling involves the following unit operations: ore storage, crushing, blending and grinding, fine ore storage, leaching, concentration, precipitation, drying, and yellowcake packaging. Radium-226 present in the uranium ore continually decays to produce radon-222. A portion of the radon-222 produced escapes from the ore in the storage area and ore handling areas and in the crushing and grinding operations that act to liberate radon-222 gas. During the remainder of the milling circuits, the ground ore is slurried, and newly formed radon-222 escapes from the extraction steps.

### Ore Blending and Storage

Ore blending ensures that the mill feed has uniform grade, which is necessary to achieve maximum efficiency in the mill circuit. Blending may be performed at either the mine or the mill. Ore is stored in a stockpile, on an ore pad, at the mill site. The storage piles provide sufficient feed for a continuous supply to the mill. Ore received from the mine often has a high moisture content; however, the dry climate typical of the major uranium districts causes rapid drying. Some storage piles are sprayed with water to maintain the moisture content and reduce dusting.

Storage pads typically cover several acres and provide ore storage to feed the mill for one or two months of operation. Some mills stockpile more ore, however. During shutdowns (standby status), however, ore usually is not kept on the storage pad. Similarly, when operations are cut back due to a depressed economy as they currently are, the quantity of ore stockpiled at the mill site is less than would be present if the mill were operating at full capacity.

### Ore Crushing

Crushing is the first stage of size reduction and involves the use of impact and/or gyratory crushers. Fine ores or undersized material bypass the crushing circuit through the use of a scalping grizzly and are conveyed directly to fine ore storage bins.

Air exhaust hoods and dust collectors are located on crushers, screens, and transfer points and exhaust air to the atmosphere via vents. Radon-222 emanating from the ore during these processes is also vented to the atmosphere. Crushing plant capacities range from 70 to 320 t per hour (NRC80).

### Fine Ore Storage

Crushed ore and undersized ore bypassing the crushers are stored in cylindrical metal fine-ore bins that are open at the top and usually about 7 to 10 m (25 to 35 feet) in diameter. Most mills have multiple bins that provide fine ore storage capacity up to double their rated daily capacity (NRC80). Radon-222 emanates from the fine ore in storage and is vented to the atmosphere.

### Ore Grinding

Belt-type feeders convey the ore from the crushing circuit to the grinding circuit, where rod and ball mills or semi-autogenous mills are used. (In a few cases, the ore may be roasted before the grinding circuit to reduce moisture for grinding, to increase the solubility of other valuable constituents (e.g., vanadium), or to improve the physical characteristics of the ore.) The ores are ground dry and then slurried with water or wet ground yielding a pulp density of 50 to 65 percent solids (NRC80). Classifiers, thickeners, cyclones, or screens are used to size the ore and return coarser particles for further grinding. The alkaline leaching process (used by one mill) requires that the ore be ground much finer (200 mesh) than for acid leaching (28 mesh).

Wet, semi-autogenous grinding is increasingly being used in place of dry crushing and rod mill grinding operations. The semi-autogenous grinder performs the ore sizing function of these operations while reducing or eliminating dry ore handling. Twelve of the 23 active or standby mills operate semi-autogeneous grinders.

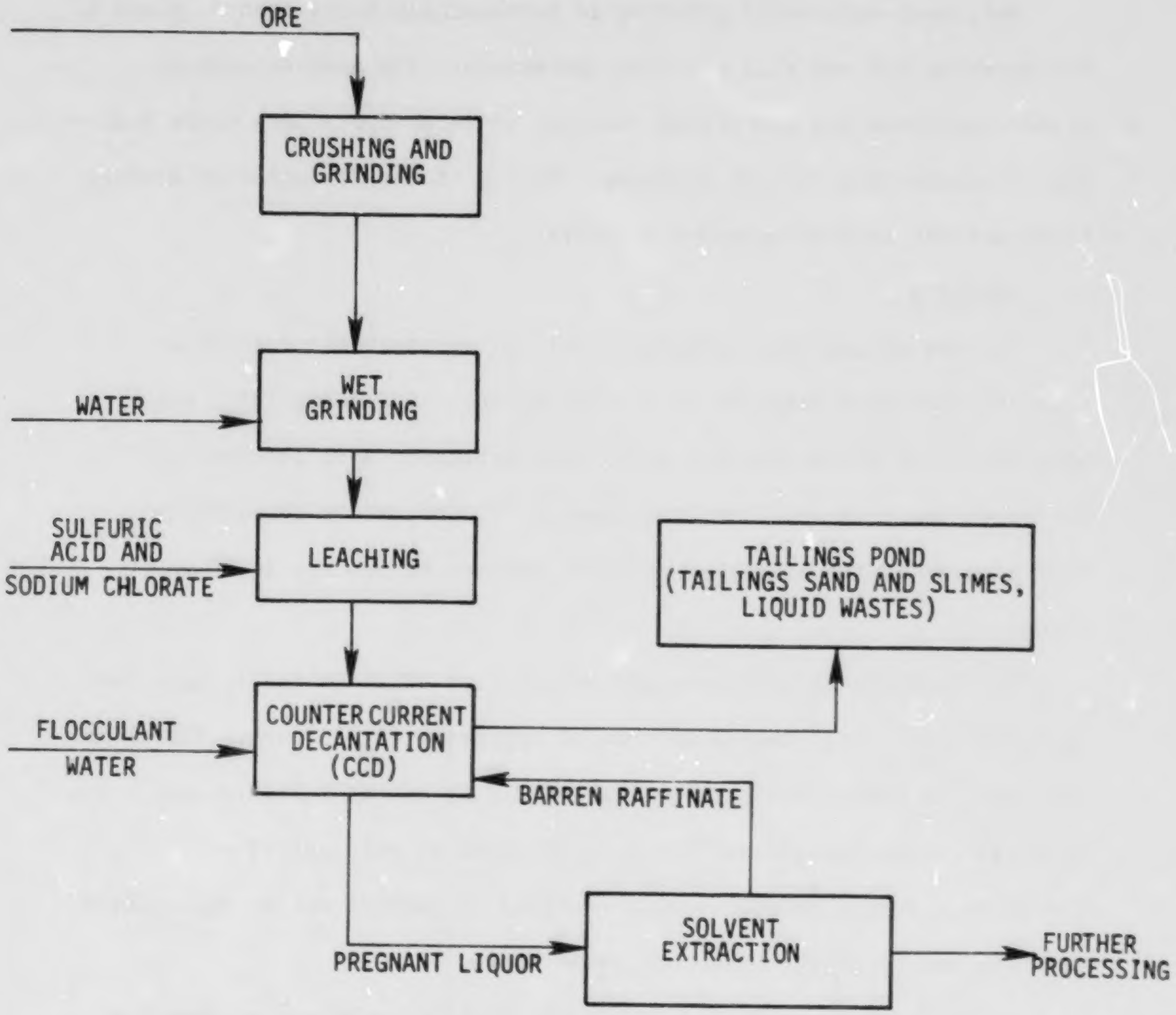
### Leaching

Hydrometallurgical leaching techniques use sulfuric acid or an alkaline carbonate solution as the lixiviant. In January 1985, eight of nine operating mills used the acid leach process. Acid leaching is preferred for ores with low lime content (12 percent or less)(NRC80). A flow diagram of the acid leach/solvent extraction process is shown in Figure 3-1.

The leaching circuit consists of a series of mechanically agitated tanks having a total residence time of approximately 7 hours. The pH in the tanks is maintained between 0.5 and 2.0 by adding sulfuric acid. The free acid concentration is from 1 to 90 grams of acid per liter during the contact period (NRC80). Acid leaching is carried out at atmospheric pressure and slightly above room temperature.

After leaching, the pregnant leach solution is separated from the tailing solids in a countercurrent decantation (CCD) circuit. The sands and slimes are pumped to a tailings pond for disposal.

Only one operating mill currently uses the alkaline leach process. Alkaline leaching, which is best suited to ores with high lime content,


ORE
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WATER
WET GRINDING
SULFURIC ACID AND SODIUM CHLORATE
LEACHING
TAILINGS POND (TAILINGS SAND AND SLIMES, LIQUID WASTES)
FLOCCULANT
WATER
COUNTER CURRENT DECANTATION (CCD)
BARREN RAFFINATE
PREGNANT LIQUOR
SOLVENT EXTRACTION
FURTHER PROCESSING

Figure 3-1. Simplified flow diagram of the acid leach process.

may be used in combination with ion exchange or caustic precipitation to concentrate and purify uranium. A flow diagram of the alkaline leach/ caustic precipitation process is shown in Figure 3-2.

The ore slurry is leached in a two-stage system (pressure leaching followed by atmospheric leaching). The leach solution contains sodium carbonate (40 to 50 grams per liter) and sodium bicarbonate (10 to 20 grams per liter). Circular tanks are used with air added to oxidize uranium to the hexavalent state. Residence time varies from 21 to 33 hours. The pregnant leach solution is separated from the tailings in a series of CCD filtrations.

### Concentration and Precipitation

Three techniques are used to concentrate uranium from the pregnant leach solution: ion exchange, solvent extraction, and the Eluex process which is a combination of ion exchange and solvent extraction. Uranium that has been concentrated by one of these methods is precipitated from solution by the addition of gaseuos ammonia ($NH_3$), sodium hydroxide ($NaOH$), hydrogen peroxide ($H_2O_2$), or magnesia ($MgO$) in several stages under controlled pH. In most mills, gaseous ammonia is used. The precipitated uranium is dewatered in thickeners and then filtered and washed in drum, plate, or frame filters. At this point, the resulting filter cake still contains considerable moisture.

### Dry/Packaging

The uranium filter cake (yellowcake) is dried in a continuous steam-heated dryer or in a multiple hearth dryer. The dried yellowcake is crushed and screened to the required size and packaged in 55-gallon drums for shipment. Some radon-222 emanates from this operation and is vented to the atmosphere with other gases.

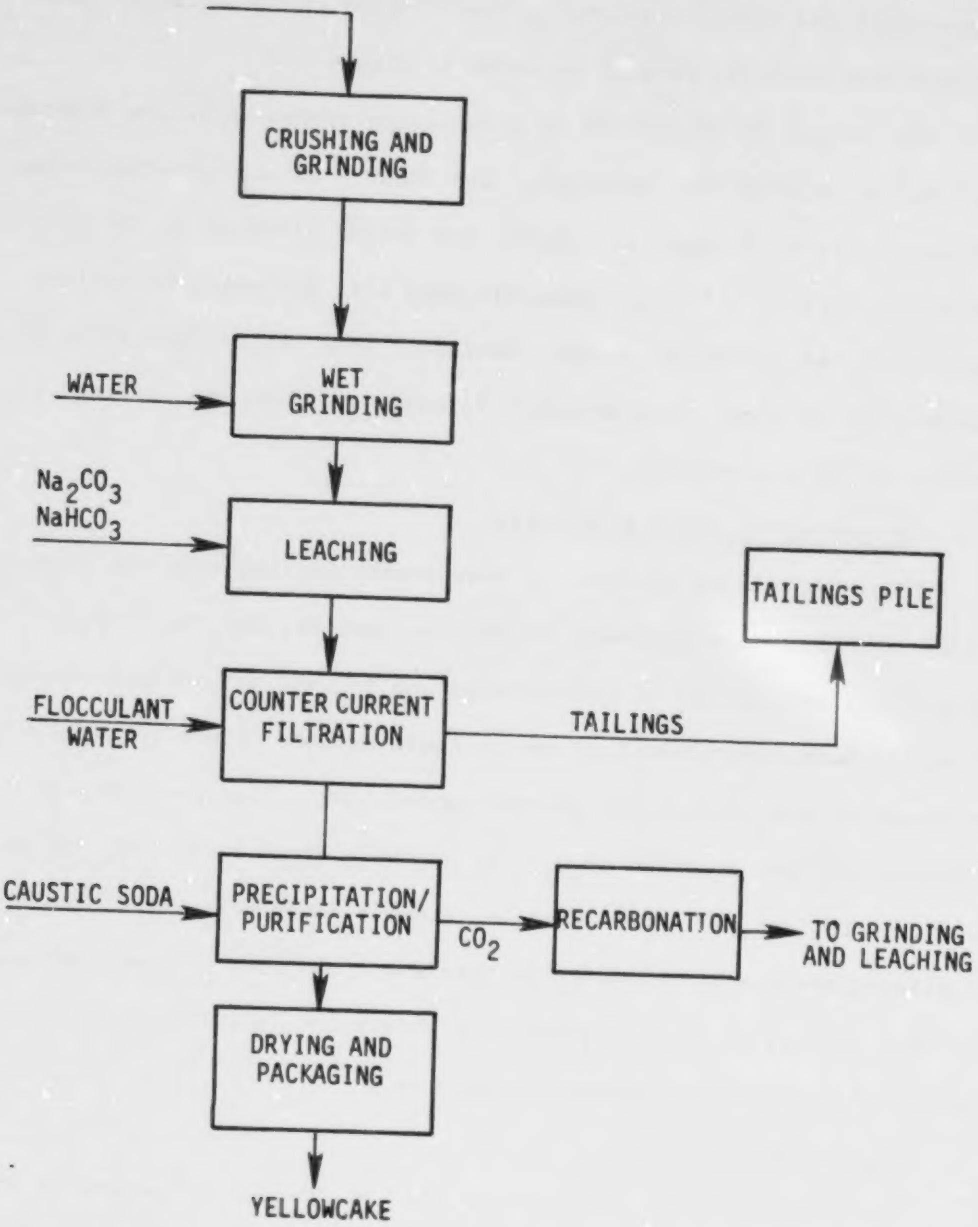

CRUSHING AND GRINDING
WATER
WET GRINDING
$Na_2CO_3$
$NaHCO_3$
LEACHING
TAILINGS PILE
FLOCCULANT
WATER
COUNTER CURRENT FILTRATION
TAILINGS
CAUSTIC SODA
PRECIPITATION/ PURIFICATION
$CO_2$
RECARBONATION
TO GRINDING AND LEACHING
DRYING AND PACKAGING
YELLOWCAKE

Figure 3-2. Simplified flow diagram of the alkaline leach-caustic precipitation process.

### 3.2.2 Tailings Management

#### Composition of Tailings

With the exception of the small weight (<0.5 percent) of uranium extracted during milling, the dry weight of the tailings represents the total weight of the processed ore. The tailings discharge is comprised of three fractions: (1) the sands, which consist of solids greater than 200 mesh, (2) the slimes, which consist of solids less than 200 mesh, and (3) the liquid, which is an aqueous solution containing milling reagents and dissolved ore solids. Dry tailings from an acid leach mill are typically composed of 20 to 37 percent slimes (NRC80). Tailings are discharged from the mill as a slurry at an average ratio, by weight, of 1:1 (solids to liquids).

About 10 percent of the uranium and virtually all of the radionuclides in the ore are discharged with the tailings. Tailings represent the largest source of radon-222 emissions during the operational phase of uranium mills. The majority of radium-226 in the tailings (up to 80 percent) is contained in the slime fraction (NRC80). Sands (38 to 200 mesh) contain radium-226 in concentrations ranging from 26 to 100 pCi/gram (NRC80). The tailings liquid contains 20 to 7500 pCi/liter of radium-226 (NRC80). Mills surveyed in this study indicated that tailings solution typically contains about 100 to 200 pCi/liter of radium-226.

#### Management Practices

Virtually all tailings are disposed of in piles; only a small percentage is used for backfill in underground mines. Current options include below-grade disposal in mined-out or specially excavated pits and above-grade disposal behind dams. The dams are constructed of earthen material or coarse tailings. Sizes of these impoundments vary from 26 to about 300 acres. A summary of the current status of tailings piles at active and standby uranium mills is presented in Table 3-2.

The majority of the tailing piles at the active and standby mills are above-grade piles. Below-grade disposal is the preferred method for new milling operations or new piles at existing mills. Below-grade disposal is preferred because of its inherent greater stability, both short and long term. In addition, tailings disposed of below grade are typically covered with water, which effectively controls dusting and reduces radon-222 emissions.

Site topography dictates the general shape of above-grade surface piles. One-, two-, and three-sided piles are constructed across valleys and along hillsides. Four-sided piles are constructed on relatively flat terrain, such as in New Mexico, where the tailings cannot be contained by the natural topography. Embankments are either constructed of earthen material or of the sand fraction of the tailings. The preferred method is earthen construction. The three common methods used when constructing a tailings embankment with tailings are the upstream, downstream, and centerline methods (Figure 3-3). The upstream method begins with a previous starter dam constructed at the downstream toe of the embankment. Tailings are spigotted from single or multiple points along the dike crest. Sand settles near the discharge point while the slime settles in the interior of the pond, thus forming a gently sloping beach. The embankment is raised in successive lifts. The centerline of the embankment crest moves in the upstream direction.

Table 3-2. Summary of the current status of uranium mill tailings piles

| Operational phase[a] | Type of pile[b] | Number of piles | Total surface area (acres) | Total ponded area[c] (acres) | Total area stabilized[d] (acres) |
|---|---|---|---|---|---|
| Active | Above-grade with earthen dams | 22 | 1934 | 909 | 550 |
| | Above-grade with tailings dams | 6 | 703 | 245 | 0 |
| | Below-grade piles | 2 | 54 | 42 | 0 |
| Inactive | Above-grade with earthen dams | 7 | 792 | 0 | 400 |
| | Above-grade with tailings dams | 1 | 40 | 0 | 8 |

---

(a) Active piles are being used for tailings disposal or will be used when a standby mill resumes operations. Inactive tailings piles have reached maximum capacity and will not be used for additional tailings disposal.

(b) Above-grade piles can be constructed using dams constructed of either earthen material or segregated coarse tailings (sands) to contain the tailings. Below-grade piles are contained in excavated pits.

(c) The portion of the total surface area that is covered with tailings solution.

(d) Tailings piles of Wyoming mills that are on standby status have been or are being covered with about 0.3 m (1 ft) of soil or overburden to prevent dusting during interim stabilization.

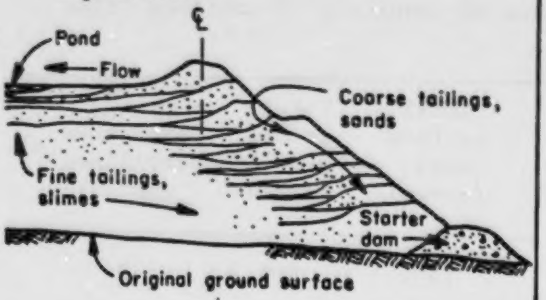
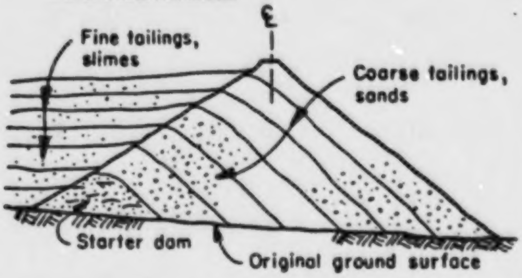
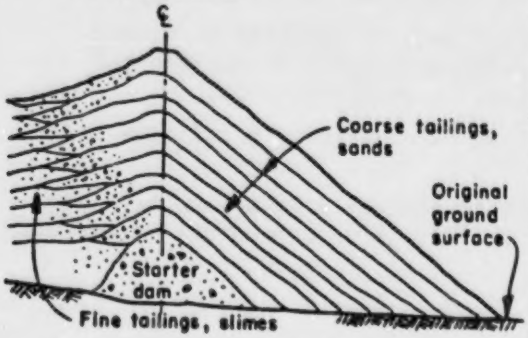
| TYPE | DESCRIPTION |
|---|---|
| Upstream<br> ℄<br>Pond<br>Flow<br>Coarse tailings, sands<br>Fine tailings, slimes<br>Starter dam<br>Original ground surface | The embankment is constructed from starter dam in lifts which are placed successively on the previous lift in the upstream direction. The centerline of embankment crest moves in the upstream direction. |
| Downstream<br> ℄<br>Fine tailings, slimes<br>Coarse tailings, sands<br>Starter dam<br>Original ground surface | The embankment building material is added successively to the downstream side of the previously placed embankment. The centerline of the crest moves in a downstream direction. |
| Centerline<br> ℄<br>Coarse tailings, sands<br>Original ground surface<br>Starter dam<br>Fine tailings, slimes | The embankment is raised in steps with the centerline of the crest remaining above the starter dam. |

Figure 3-3. Embankment construction using coarse tailings (BM 82).

The downstream method of embankment construction begins with an impervious starter dam constructed at the toe of the embankment. Cycloned tailings (sands) are used to build the embankment on the downstream side, and the overflow (slimes) is piped to the pond on the upstream side. The embankment is raised in successive lifts such that the centerline of the embankment crest moves in the downstream direction (Figure 3-3). This method is considered more stable than the upstream method because the sands and slimes do not intermix and the embankment is not raised upon unconsolidated material of low shear strength.

The centerline method of construction begins with an impervious starter dam constructed at the center of the embankment. Cycloned tailings are distributed equally on the upstream and downstream side of the embankment while the overflow (slime) is piped to the pond. The embankment lifts are constructed such that the centerline of the embankment crest remains above the starter dam (Figure 3-3).

The water level in a tailings pile is controlled through the use of decant towers, pumps, or siphons. Evaporation is also important in controlling pond level. Water reclaimed from tailings impoundments is sometimes recycled in the mill.

## 3.3 Site-Specific Characteristics

Brief, site-specific summaries prepared as part of this project for each active or standby conventional uranium mill are presented in this section. The summaries focus largely on the tailings disposal operation because they represent the largest source of radon-222. These summaries were compiled from data contained in previous documents and, in most cases, confirmed or updated through correspondence with the operators.

The site descriptions are organized by state. Most of the information presented in the site descriptions was taken from a recent NRC profile of licensed mills (NRC84); information or data from other sources is referenced separately. Results of a 1983 survey of populations living within a 5-km (3.1-mile) radius of each tailings pile are referenced in each site description (EPA83b). The detailed results of that survey are included in Appendix A. Estimates of the areas (in acres) associated with tailings piles are given for each site. These estimates are often taken from sources of information that are 3 to 5 years old. When site operators could supply updated or more accurate information, it was included. The estimates of size are approximate. The accuracy of these measurements is not defined but is likely to be ±10 percent or more. This is important because the size of the piles is a controlling factor in radon-222 emissions. Radon-222 emissions are based on estimates (in $m^2$) of different areas of the piles (unsaturated, saturated, water covered). For this reason the accuracy of any estimate of radon-222 emissions from these tailings piles is limited by the accuracy of the measurements of area. In addition, another major parameter used in estimating radon-222 emissions is the radium-226 content of the source (e.g. ore, sand tailings, slimes). In many cases a reliable estimate or measurement of this constituent is not available at licensed sites. A previous EPA report (EPA83b) contains estimates of average radium-226 contents of tailings at each site. However, several site operators indicated these values are questionable. Values for radium-226 content are given in the following discussion when they were available from the site operator.

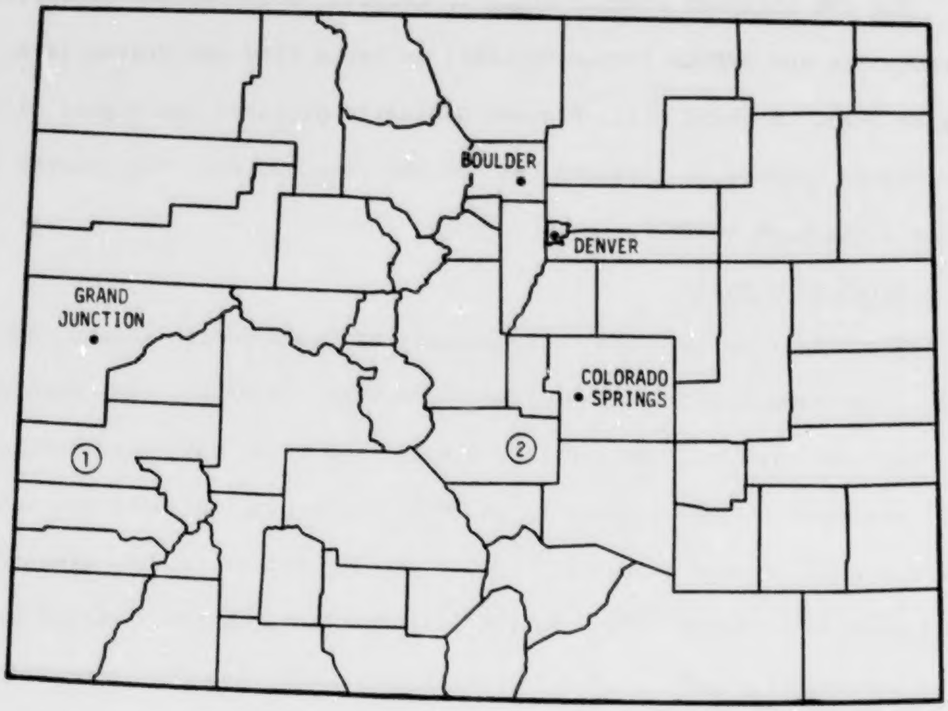
### 3.3.1 Colorado

The two licensed uranium mills in Colorado are operated by Cotter Corporation and UMETCO (Union Carbide) in Canon City and Uravan (see Figure 3-4). A third mill, Pioneer Nuclear's proposed San Miguel mill in San Miguel County, is licensed but not yet constructed. The license is under litigation (NRC84).

#### Canon City Mill

The Cotter Corporation, a subsidiary of Commonwealth Edison, operates a two-stage acid leach mill at Canon City, Colorado, that recovers uranium and vanadium. Originally, a small [68 t per day] alkaline leach mill was constructed on the site in 1968. This original mill was subsequently modified and expanded to 360 t per day before it was permanently shut down in December 1979. During its operation, Cotter produced uranium for sale to both the Federal Government (AEC) and the commercial market. The AEC tailings were commingled with tailings from production for commercial sales. The existing acid leach mill was built on the same site and began operations in September 1979. It has a capacity of 1100 t per day, and the average ore grade is 0.4 percent $U_3O_8$. In January 1985, the mill was temporarily shut down and put on standby status. Cotter plans to reopen the mill in June or July 1985 (Mc85). Production is planned for a 10 days up, 4 days down cycle, running near capacity when operating.

Tailings generated since September 1979 have been placed in an above-grade clay- and membrane-lined pile. This main pile covers 100 acres (Mc85). A dam constructed of liner cover, Hypalon liner, clay liner, sand chimney drain, and earthen shell (upstream to downstream


BOULDER
DENVER
GRAND JUNCTION
COLORADO SPRINGS
①
②

1. Union Carbide
   Uravan Mill

2. Cotter Corp.
   Canon City Mill

Figure 3-4. Location of mills in Colorado.

section) was built across the drainage to contain the tailings. This primary dam will be raised to its ultimate height of 35 m (115 feet) in one additional stage. Tailings solution covers virtually all of the 100 acres and varies in depth from less than 0.3 to more than 6 m (<1 to 20 feet). Currently, the area of exposed tailings beach is approximately 0.2 acre (Mc85). The tailings discharge into the pond is moved along the dike to keep the tailings wet and evenly distributed. The tailings are reported to contain 780 pCi/g of radium-226 (EPA83).

A secondary pile has been constructed adjacent to the main pile. These pile are actually two cells of one large pile. In 1981, Cotter began moving the commingled tailings generated in pre-1979 operations from old tailings piles into the secondary pile. This transfer of 1.4 x $10^6$ t of commingled tailings has been completed (DOE82). The secondary pile is now used for disposal of non-tailings solid waste generated on site and will be used for disposal of decommissioning waste during closure operations (DOE82). The old tailings have not been covered, but have been furrowed to control dusting. The orientation of the mill and the tailings piles is shown in Figure 3-5.

About 0.9 x $10^6$ t of mill tailings are currently under management at this site (NRC84). The costs to construct the main and secondary piles were $15,800,000 and $7,200,000, respectively (DOE82).

Canon City is located about 3.2 km (2 mi.) north of the mill site. The area immediately surrounding the mill site is unpopulated, and the predominant land use is livestock grazing (DOE82). The edge of the nearest residential area is approximately 2.4 km (1.5 mi.) northeast of the mill (DOE82). A 1983 survey indicated 5933 people living within 5 km

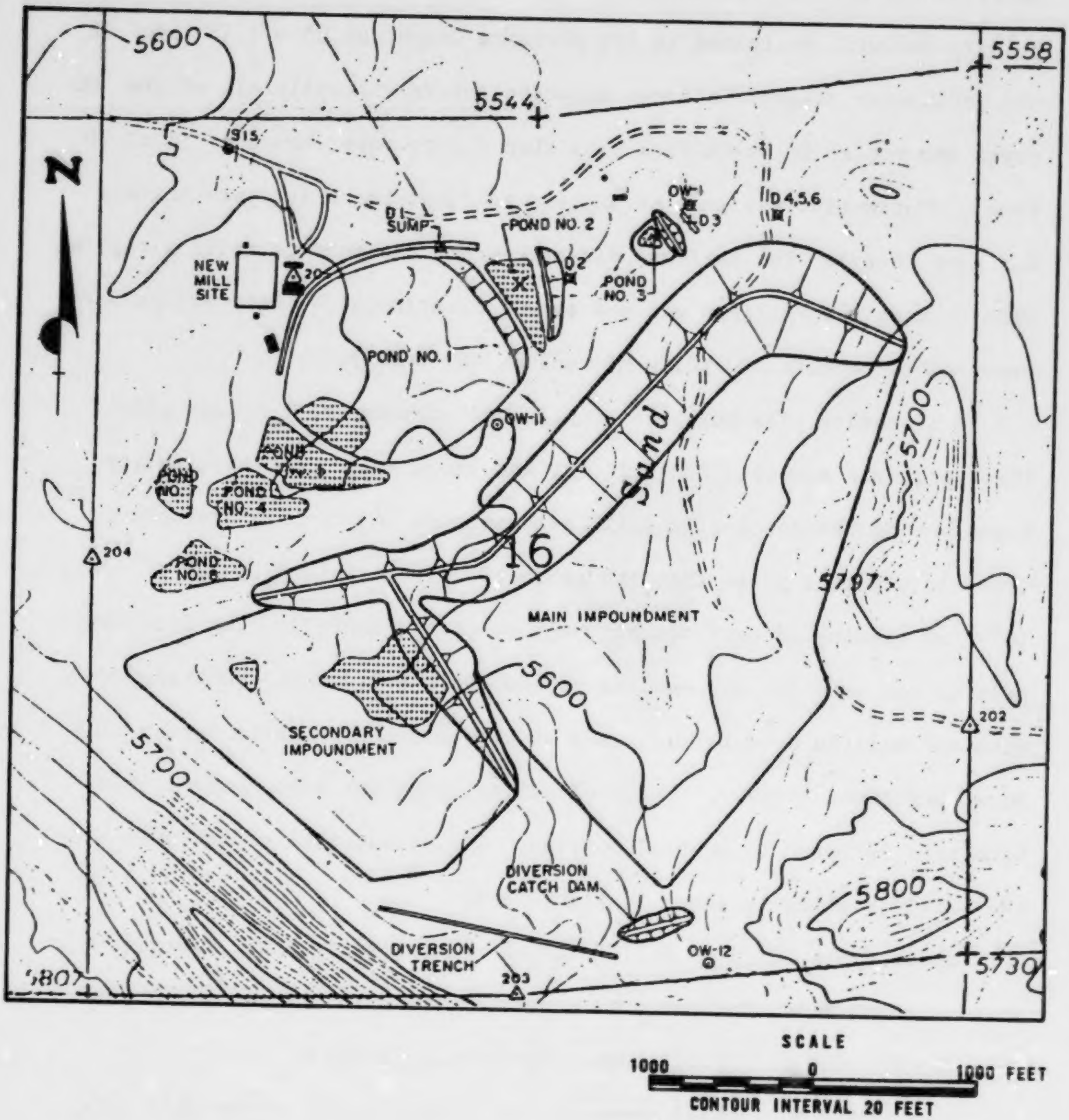

5600
5544
5558
N
515
D1 SUMP
POND NO. 2
OW-1
D3
D 4,5,6
NEW MILL SITE
20
D2
POND NO. 3
POND NO. 1
OW-11
POND NO.
POND NO. 4
POND NO. 6
204
Sund
16
5700
5797
MAIN IMPOUNDMENT
5600
SECONDARY IMPOUNDMENT
5700
202
DIVERSION CATCH DAM
5800
DIVERSION TRENCH
OW-12
203
5807
5730
SCALE
1000
0
1000 FEET
CONTOUR INTERVAL 20 FEET

Figure 3-5. Orientation of the Cotter tailings piles and mill site.

Note: Tailings in Pond No. 1 have been moved to a secondary impoundment. Tailings are contained in main and secondary impoundments. Other ponds contain process waters.

(3.1 mi.) of the tailings pile (EPA83b). The same survey indicated no population within 2 km (1.25 mi.).

The climate in the area is semiarid and temperate with an average annual precipitation of 12 inches (DOE82). Wind speeds are variable with a mean of 8 miles per hour (DOE82).

### Uravan Mill

The Union Carbide Mill is located in Uravan, Colorado, an area of rugged canyons and mesas. It is 80 km (50 mi.) south of Grand Junction. Uranium, vanadium, and radium-226 recovery operations began at this site in 1915. Union Carbide has owned and operated the facility since 1936. In November 1984 the Uravan Mill went on standby status and is not currently operating. The plant plans to be down for 2 years, possibly permanently (Kr85). The tailings disposal facility has reached its maximum capacity, and a new disposal area must be planned and approved prior to restarting mill operations (Kr85). The capacity of the mill is 1200 t of ore per day.

The mill uses a hot, highly oxidizing, two-stage acid leach to recover uranium and vanadium. During past milling operations, ore has been received from more than 200 mines in the Uravan mineral belt. Tailings have been generated under AEC, Army, and commercial contract and have been commingled and disposed of on site. Three tailings piles contain an estimated $9 \times 10^6$ t of tailings. These piles are situated on mesas above Uravan. Piles 1 and 2 are adjacent and overlapping and actually constitute just one pile. The piles are constructed behind dikes of coarse tailings on the outward face and contained by the native terrain on the inward side. Tailings are discharged to the piles from spigots situated around the brim. Gravity settling deposited the sands near the dike, and slimes were carried to the interior with the tailings solution.

Piles 1 and 2 cover a combined 58 acres, and have a height of about 46 m (155 ft) (DOE82). Pile 3 covers 22 acres and the dike is about 33 m (110 ft) high. The EPA EIS reported the radium-226 content of the tailings at Uravan to be 480 pCi/gram (EPA83b); additional details on this parameter were not found during this study.

The Uravan operation utilizes several other ponds in its flow scheme. Six solvent extraction (SX) raffinate evaporation/seepage ponds receive barren solution from the vanadium SX section. Residue in these ponds will be placed in the tailings ponds at closure. The SX ponds cover 36 acres (NRC84).

A site map or diagram showing construction of the tailings piles was not available for inclusion in this report.

The general area is sparsely populated. A 1983 survey indicated 147 people were living from 0.5 to 1.0 km (0.3 to 0.6 mi.) away from the tailings piles (EPA83). Additionally, 193 people are reported to live between 1.0 and 2.0 km (0.6 and 1.2 mi.) away (EPA83b). Only nine other people are reported to live within 5 km (3.1 mi.), for a total of 349 people (EPA83).

The climate at Uravan is semiarid, with only about 10 inches of precipitation a year. The tailings must be kept moist to prevent blowing of dust (DOE82). Evaporation is about 56 inches per year (EPA83b).

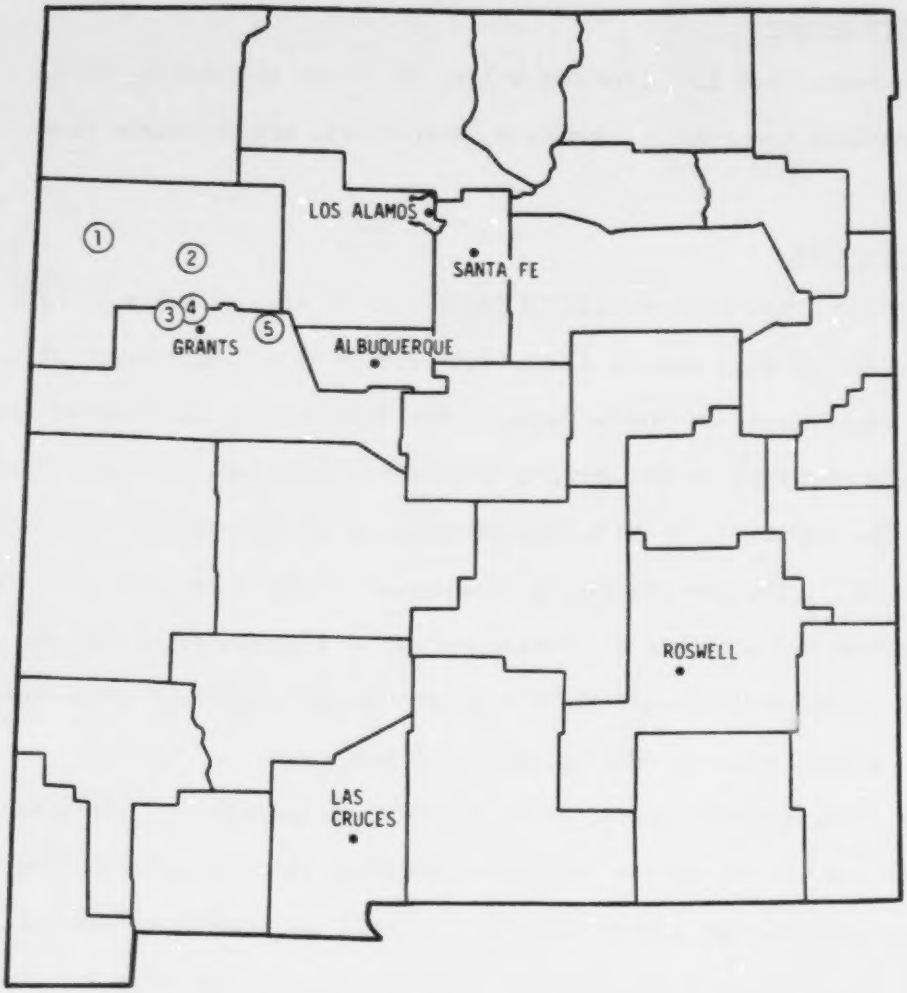
### 3.3.2 New Mexico

New Mexico has five licensed mills, which are operated by Sohio, United Nuclear Corporation, Anaconda, Kerr-McGee, and Homestake (see Figure 3-6).

#### L-Bar Mill

Sohio's L-Bar Uranium Mill is located in an area of hilly terrain about 71 km (44 mi.) west of Albuquerque and 16 km (10 mi.) north of Laguna, New Mexico, in Cibola County. Ore for the mill is obtained from an underground mine in the Jackpile sandstone formation. The acid-leach mill began operations in 1976, but has been on standby status since May 1981 (NRC84). The ore processing capacity of the mill is 1500 t per day. Ore reserves are adequate to provide for 10 to 15 years of operation. The ore grade varies from 0.05 to 0.30 percent $U_3O_8$ (NRC84). Size reduction is accomplished by semi-autogenous grinding.

Mill tailings are contained in a single tailings pile. The L-Bar tailings dam was one of the last dams permitted in the industry using the upstream construction method (Jo80). The tailings impoundment is built above grade using an earthen starter dam to the west that keys into natural topography on the north and south. A smaller saddle dam is constructed to the east. A simplified diagram of the tailings pile is presented in Figure 3-7. Tailings have been discharged to the pond from a single pipe that was uniformly moved along the dam. Coarse sands settled near the dike while slimes (that fraction of tailings passing a No. 200 sieve) deposited in the interior area. The slimes constitute about 25 percent of the total tailings. Water was decanted and pumped back to the mill. During operations, the edge of the tailings solution



①
②
③
④
⑤
LOS ALAMOS
SANTA FE
GRANTS
ALBUQUERQUE
ROSWELL
LAS CRUCES

1. United Nuclear Corp.
   Churchrock Mill
2. Kerr-McGee Nuclear Corp.
   Ambrosia Lake Mill
3. Homestake Mining Co.
   Homestake Mill
4. Anaconda Minerals Co.
   Bluewater Mill
5. Sohio
   L-Bar Mill

Figure 3-6. Location of mills in New Mexico.

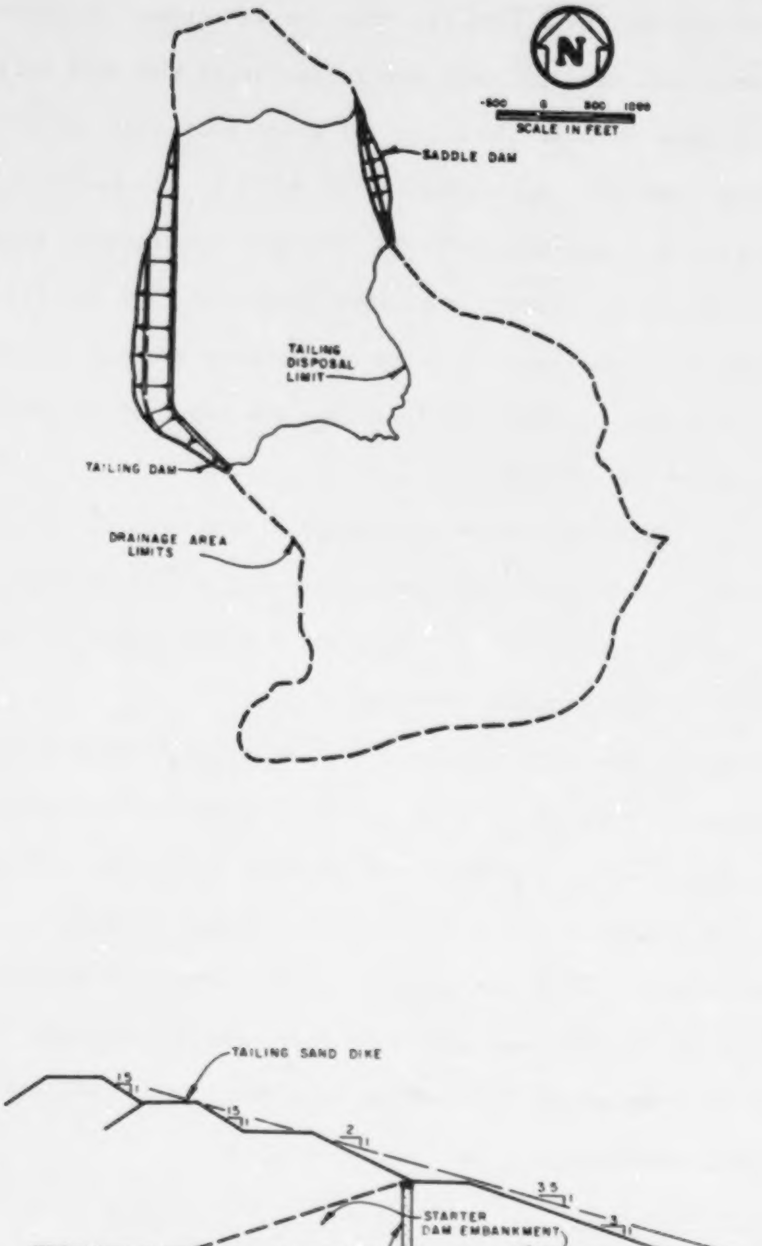

N
-500 0 500 1000
SCALE IN FEET
SADDLE DAM
TAILING DISPOSAL LIMIT
TAILING DAM
DRAINAGE AREA LIMITS
TAILING SAND DIKE
1.5
1
1.5
1
2
1
3.5
1
3
1
STARTER DAM EMBANKMENT
CHIMNEY DRAIN
NATURAL GROUND
FINGER DRAIN

Figure 3-7. Configuration of the tailings pile at Sohio's L-Bar mill, and a cross-section through the dam.

was maintained about 60 m (200 ft) from the dam crest. A light-track pressure dozer was used to construct raises using the sand tailings. The total impoundment area is 180 acres, of which about 125 acres are covered with tailings (NRC84). Approximately 60 acres of the tailings are covered with tailings solution (NRC84). The pile consists of about 1.5 x $10^6$ t of tailings and reaches a maximum height of 15 m (50 ft) (NRC80). The facility was designed to provide an ultimate storage capacity of 6.8 x $10^6$ t of tailings (Jo80). The tailings are reported to contain 500 pCi/g of radium-226 (EPA83b).

During operations, ore is stockpiled at the mill on an ore pad and apron feeder. Since the plant went on standby status in 1981, ore has not been stored on these areas. However, a short supply of ore has been stored north of the tailings area (NM85).

The area is sparsely populated. A 1983 survey indicated that no population resided within a 3-km (1.9-mi.) radius of the tailings pile (EPA83). Reportedly, 42 people live between 3 and 4 km (1.8 and 2.5 mi.) away and 129 between 4 and 5 km (2.5 and 3.1 mi.) (EPA83b).

Meteorological data are available from two onsite measuring stations in addition to the Kirtland Air Force Base near Albuquerque. The EPA collected meteorological data at the mill for 1 year (1978-1979) for a radiological assessment.

### Church Rock Mill

United Nuclear's Church Rock Mill is located 32 km (20 mi) northeast of Gallup, New Mexico, on an alluvial plain situated near an arroyo. The mill, which opened in 1977, is designed to use acid-leach extraction to process about 3600 t of ore per day from the company-owned underground mines. The ore contains 0.035 to 0.12 percent $U_3O_8$, in a sandstone matrix. Fresh water for mill operations is obtained from underground mines. Yellowcake is the only mill product. The mill is currently inactive and on standby status.

The tailings pile is formed by a dam built from native clays and compacted coarse tailings. The pile has three compartments separated by earthen embankments. The total surface area of tailings, including the dam and a stormwater interceptor ditch, is 100 acres. About half of the area is in use. The surface area of liquid on the tailings pile is minimal. The maximum depth of tailings is about 15 m (50 ft). The storage capacity of the pond is about $10 \times 10^6$ $m^3$ ($365 \times 10^6$ $ft^3$). The available evaporative area is 160 acres. The tailings are reported to contain 290 pCi/g of radium-226 (EPA83b).

A site map or diagram of the construction of the tailings pile was not obtained for inclusion in this report.

The area around the mill is sparsley populated. A 1983 survey indicated that 25 people reside within 2 km (1.25 mi.) and 77 live within 3 km (1.9 mi.). The survey indicated that 213 people live within 5 km (3.1 mi.) but none live within 1 km (0.6 mi.) (EPA83b).

In July 1979, a break in the tailings dam caused about $350 \times 10^6$ liters ($93 \times 10^6$ gal) of effluent and 1000 t of tailings to spill on or into nearby soil and streams. This spill resulted in the release of almost all of the impounded liquid but less than 1 percent of the solids. The streams carried the spilled tailings to Rico Puerco, through Navajo grazing lands, and finally into Arizona. The mill was closed from July 1979 until fall 1979 while measures were taken to clean up the spill to a stream. The cleanup of the stream has been completed. The mill has been inactive since 1982, and corrective action to clean up the groundwater is continuing.

Bluewater Mill

Anaconda's Bluewater Uranium Mill is located in the Grants Mineral Belt about 16 km (10 mi.) northwest of Grants, New Mexico. The site is in a small valley characterized by an undulating, relatively level surface with gentle swales and small rounded hills (DOE82). The mill was originally constructed in 1953 and operated until 1982 when it went to standby status. Since 1953, the milling operations have gone through several major modifications. Originally, a carbonate leaching process was used. In 1955 parallel mill circuits were provided for both alkaline and acid leaching of limestone and sandstone ores. The carbonate mill was shut down in 1959. Capacity has been expanded to 5400 t of ore (0.06 to 0.07 percent $U_3O_8$) (DOE82). Production has been for both AEC (1956 to 1970) and commercial contracts. Through 1981, the Bluewater mill has processed more than $21.4 \times 10^6$ t of ore ranging from 0.06 to 0.60 percent $U_3O_8$ (DOE82).

The mill site has three tailings piles. The carbonate tailings from early operations were deposited in an area immediately northwest of the mill in a flat-lying pile covering about 47 acres (DOE82). The inactive pile has been covered with native soil to an average depth of 0.8 m (2.5 ft) (DOE82). Other tailings from the early carbonate processing were emplaced in what is now the main tailings pile for acid tailings. A second tailings pile, the north area acid pile, is situated immediately northwest of the main pond. It covers 24 acres and was also covered in 1977 with about 0.8 m (2.5 ft) of native soil (DOE82).

The main pile was put in operation in 1956 and covers about 270 acres. The dam surrounding the pond is constructed of compacted natural soils and alluvium and is about 18 m (60 ft) high at the south end and 6 m (20 ft) high at the north end (DOE82). Tailings are discharged along the southern part of the dam. About 23 x $10^6$ t of tailings are in this pile (NRC84). A radiological assessment of the Bluewater mill conducted by the State of New Mexico indicated that the area of dry tailings in the main pond was 91.4 acres, the area of wet beaches was 24.0 acres, and the area covered by tailings solution was 21.7 acres (NM85). An additional 130 acres represents the area of old tailings in this pile.

The specific activity for radium-226 in the old tailings is reported to be 520 pCi/gram and 280 pCi/gram in the tailings in the main pond (NM85). The radiological assessment conducted by the State of New Mexico indicated that during operations the ore pad, main pond, and carbonate tailings contribute about 850, 12,000, and 1940 Ci/yr of radon-222, respectively, for a total of 15,000 Ci/yr of radon-222 (NM85).

A site map or diagram of the tailings pile was not available for inclusion in this report.

The area around the Bluewater Mill is sparsely populated. A 1983 survey indicated that 907 people lived within 5 km (3.1 mi.) of the mill (EPA83b). Of this total, 142 lived within 3 km (1.9 mi.).

Annual precipitation averages 8.8 inches--most as rain but some as snow. Wind is channeled through the valley in a westerly direction. The site is in the "southwest mountains" climatological subdivision of New Mexico.

## Homestake Mill

The Homestake Mill is 16 km (10 mi.) northwest of Grants, New Mexico. The mill began production in 1958. Its early capacity has been increased over the years from 675 t to its present 3200 t of ore per day (DOE82). The Homestake Mill is the only active uranium mill using the alkaline leach process. Current milling operations have been cut back to a milling rate of about 450 t of ore per day. The ore grade milled at Homestake has ranged from 0.04 to 0.30 percent $U_3O_8$ (DOE82).

The mill site is relatively flat and covers about 1500 acres. Two tailings piles, one active and the other inactive, are located on site (Figure 3-8). The inactive pile contains tailings generated between 1958 and 1962 under AEC contracts. The $1.1 \times 10^6$ t of AEC tailings cover about 40 acres and are contained within an 8-m (25-ft) high earthen embankment (DOE82). There is no ponded tailings solution and the pile has been dry for some time. Approximately 20 percent, 8 acres, of this tailings pile has been covered with a few feet of contaminated soil excavated from an area affected by a past spill from the active pile (DOE82). Efforts have been made to revegetate the pile in order to reduce dusting.

The active pile contains about $18 \times 10^6$ t of commingled tailings. The pile has the shape of a large rectangular-base prism that rises above the flat ground surface (DOE82). It covers 170 acres and is about 26 m (85 ft) high. The slopes of the four sides are about 2:1 (h:v). The top of the pile is divided into two cells that are used alternately for tailings discharge. Most of the interior of both cells is covered with tailings solution. The total surface area of the ponded fluid in these

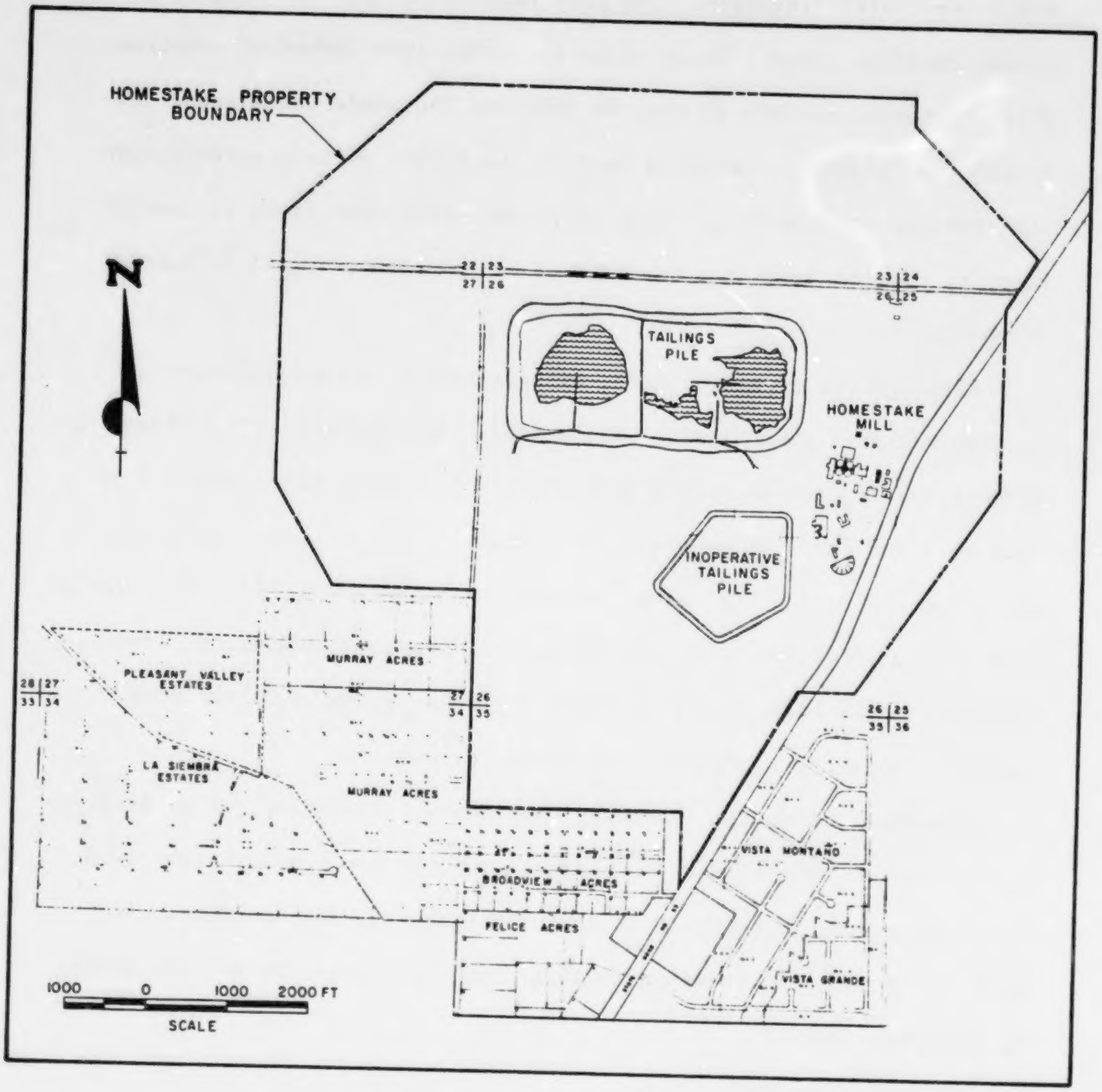

HOMESTAKE PROPERTY BOUNDARY
N
22 | 23
27 | 26
23 | 24
26 | 25
TAILINGS PILE
HOMESTAKE MILL
INOPERATIVE TAILINGS PILE
MURRAY ACRES
PLEASANT VALLEY ESTATES
28 | 27
33 | 34
27 | 26
34 | 35
26 | 25
35 | 36
LA SIEMBRA ESTATES
MURRAY ACRES
VISTA MONTAÑO
BROADVIEW ACRES
FELICE ACRES
VISTA GRANDE
1000 0 1000 2000 FT
SCALE

Figure 3-8. Diagram of the Homestake mill site and adjacent residential area.

two cells is about 100 acres. Homestake maintains a 15-m (50-ft) beach and 1.5-m (5-ft) freeboard. The pile embankments are constructed of coarse tailings (sands) built up by the centerline method of construction. A mobile cyclone is used to separate the sands and slimes. Decanted pond liquid is recycled back to the mill. Surface water sprays and chemical treatments are applied to the embankment faces to inhibit dusting. The tailings are reported to contain 385 pCi/g of radium-226 (EPA83b).

Although the area around the mill is rural, two subdivisions are located within 1.6 km (1 mi.) of the mill. Homestake's 1982 license renewal application indicated that there was no population within 1 km (0.6 mi.) and that 145 people lived between 1 and 2 km (0.6 to 1.2 mi.) away from the mill. The survey counted a population of 575 people within 5 km (3.1 mi.) of the mill. Homestake has purchased additional land adjacent to the mill site to provide a 0.8-km (0.5-mi.) buffer zone (DOE82). Appendix A presents population survey data.

Homestake is in the "southwest mountains" climatological subdivision of New Mexico. The climate is characterized by low precipitation (8.8 inches/yr average), sunny days (75 to 80 percent), low humidity, wind gusts to 50 mph, and moderate temperatures with large diurnal and annual fluctuations (DOE82).

### Ambrosia Lake Mill

The Kerr-McGee (Quivira) mill is on standby status. It is the largest mill in the country. Ambrosia Lake is a flat area of the Grants Mineral Belt about 40 km (25 mi.) north of Grants, New Mexico. The mill began operation in 1958 with a capacity of 3270 t of sandstone ore per day. It can now handle 6350 t per day (NRC84). The milling operation involves the sulfuric acid leach process.

All of the solid tailings from the mill are contained in two piles, Tailing Piles Nos. 1 and 2. Pile No. 1 is the active area for deposition of tailings. It extends southeasterly from the mill for about 1370 m (4500 ft); its greatest width is about 820 m (2700 ft), and the outside birm ranges from 8 to 27 m (25 to 90 ft) above ground level (DOE82). An earthen starter dike was used along with the upstream method of tailing disposal. Tailings are discharged to the pond from multiple spigots located along the crest at 9-m (30-ft) intervals. The bulk of the sands are deposited on a beach inside the berm; the slimes and liquid flow into the central depression forming a lake (DOE82). The operator maintains a 150-m (500-ft) wide beach and a 1.5 m (5 ft) freeboard. Pile No. 1 covers about 260 acres and contains a liquid covered area of about 90 acres (DOE82). Another document indicates the total active tailings area is to be 250 acres with about 40 acres covered by tailings solution (NRC84).

Tailings Pile No. 2 covers about 65 acres and is west of and contiguous with Pond No. 1 (DOE82). Pile Nos. 1 and 2 have been in use since 1958. Some tailings are used as backfill in a nearby underground mine. The two piles contain approximately 24 x $10^6$ t of tailings. The tailings are reported to contain 620 pCi/g of radium-226 (EPA83b). A site map or diagram of the tailings piles was not available to be included in this report.

The area surrounding the mill is sparsley populated. A 1983 survey indicated only one person living within 5 km (3.1 mi.). This resident lived between 2 and 3 km (1.2 and 1.9 mi.) from the pile.

Precipitation averages 8.8 inches per year (DOE82). Local winds are channeled by the valley and gusts can exceed 80 km (50 mi.) per hour. Relative humidity ranges from 65 percent at sunrise to 30 percent by afternoon but often drops to 15 percent.

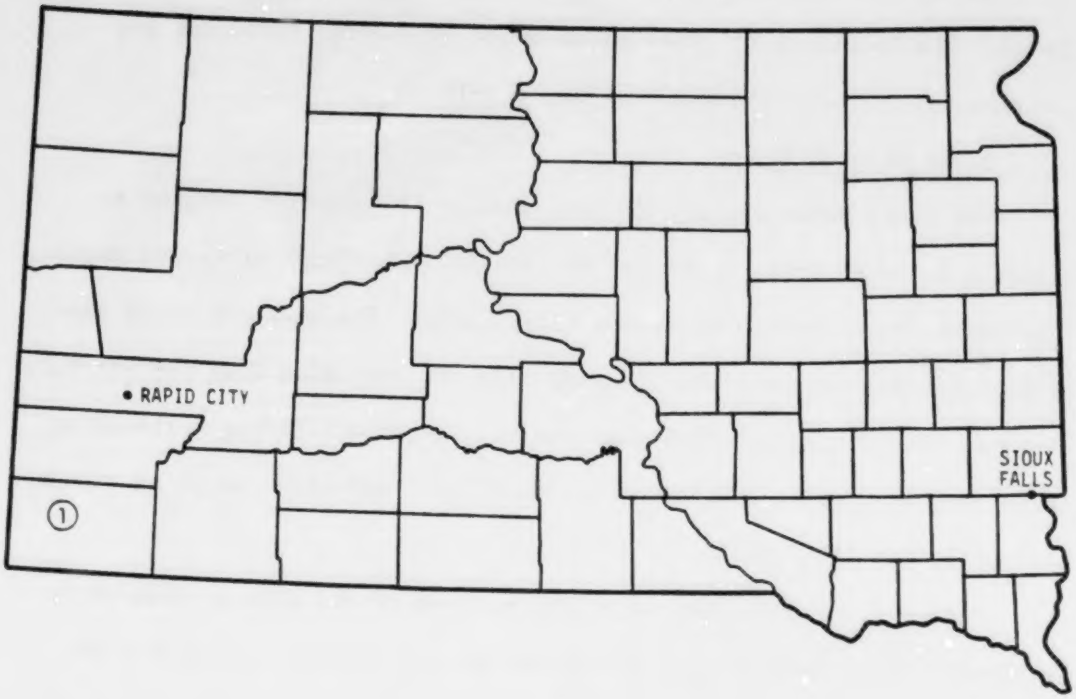
### 3.3.3 South Dakota

One licensed mill, the Tennessee Valley Authority's Edgemont mill, is in South Dakota. The location of this mill is shown in Figure 3-9.

#### Edgemont Mill

TVA's Edgemont, South Dakota mill is licensed but is in the decommissioning phase. Mill tailings are being excavated and hauled to a new permanent pile located about 3 km (2 mi.) from the mill site (NRC84). Decommissioning activities began in September 1983. About seven years will be required to complete the project (NRC84). The new pile is partially below grade and excavated into shale. An earthen embankment will contain the tailings, which will be covered with a minimum of 1 m (3 ft) clay cap and 3 m (10 ft) of topsoil. The tailings are reported to contain 560 pCi/g of radium-226 (EPA83b).

A 1983 population survey indicated that 31 people lived within 0.5 km (0.3 mi.) of the tailings pile (EPA83b); 38 others lived between 0.5 and 1.0 km (0.3 and 0.6 mi.). The same survey also indicated that 1125 people lived between 1 and 2 km (0.6 and 1.2 mi.) away from the pile and that 227 lived between 2 and 5 km (1.2 and 3.1 mi.) away (EPA83). A site map or diagram was not available for inclusion in this report.


RAPID CITY
SIOUX FALLS
①

1. Tennessee Valley Authority
   Edgemont Mill

Figure 3-9. Location of the Edgemont Mill.

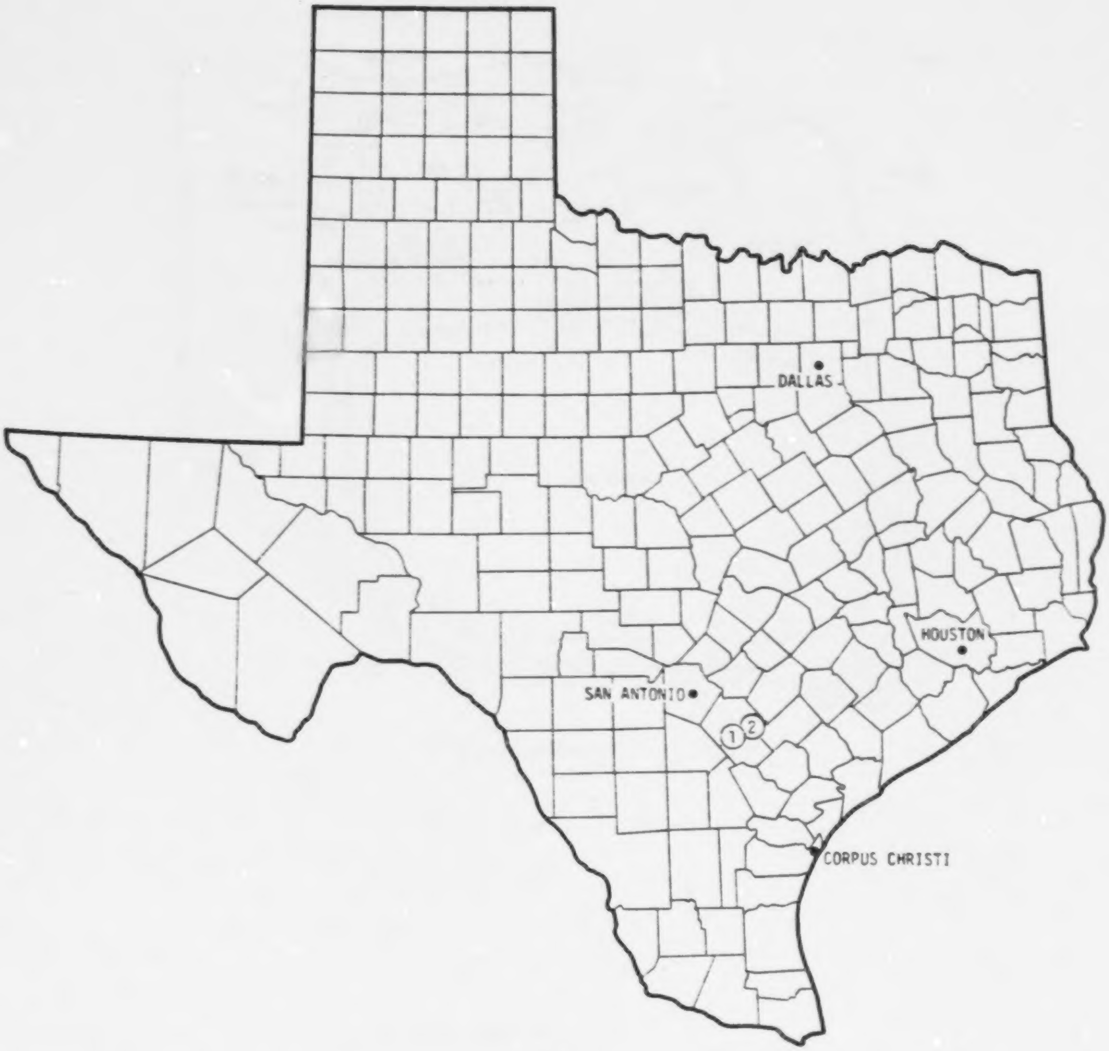
### 3.3.4 Texas

One active mill and one mill that is decommissioning are located in Texas. The locations of these mills owned by Chevron Resources and Continental Oil are indicated in Figure 3-10.

#### Panna Maria Mill

The Panna Maria Uranium Project of Chevron Resources Company is located in South Texas about 160 km (100 mi.) northwest of Corpus Christi and 10 km (6 mi.) north of Karnes City, Texas. The mill processes about 2300 t per day of a mixture of sandy clay ore averaging 0.05 percent $U_3O_8$ (Ma85). The facility, which uses semi-autogeneous grinding followed by acid leaching, began operation in January 1979 and plans to go on standby status in May 1985 (Ma85).

Tailings are contained in a single above-ground pile surrounded by earthen dikes. Material for the dikes was excavated from the area beneath the pile. The tailings area is approximately 140 acres, 20 to 25 percent (about 30 acres) of which is exposed beach; about 110 acres are covered with tailings solution (Ma85). There are approximately $3.0 \times 10^6$ t of tailings in the pile. The pile was designed to contain all tailings that are projected to be generated over the life of the mill. The maximum height of the earthen dam surrounding the pile is 19 m (62 ft), the crest width is 6 m (20 ft), and the downstream slope is 3:1 (h:v). Maximum storage of tailings in this impoundment is designed to be $9 \times 10^6$ t (Br80). The average density of the tailings is 1.2 $t/m^3$ and the specific gravity is 2.55 (Fr80). A diagram of the tailings pile and dike is presented in Figure 3-11.


DALLAS
HOUSTON
SAN ANTONIO
CORPUS CHRISTI
①
②

1. Conoco/Pioneer Nuclear
   Conquista Project

2. Chevron Resources Co.
   Panna Maria Mill

Figure 3-10. Location of mills in Texas.

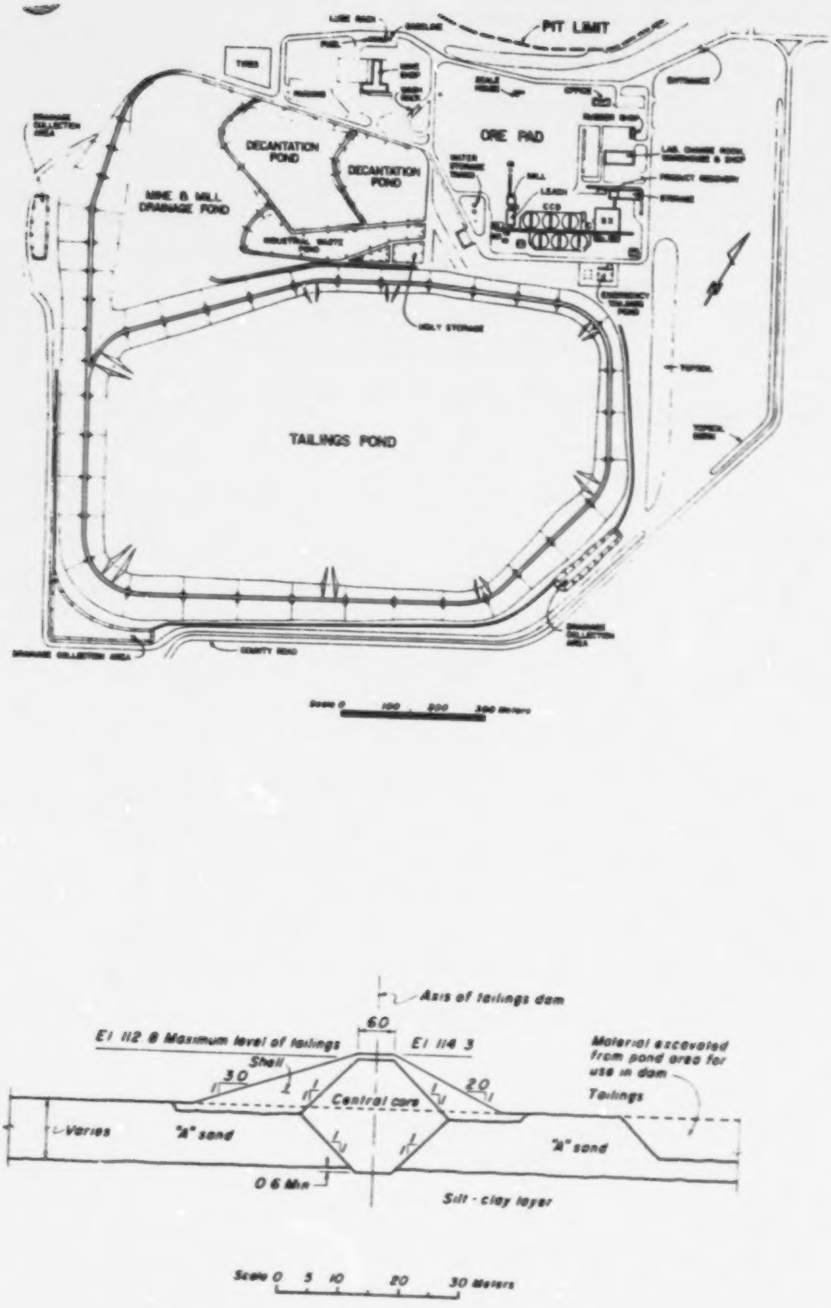

PIT LIMIT
ORE PAD
DECANTATION POND
DECANTATION POND
MINE & MILL DRAINAGE POND
INDUSTRIAL WASTE POND
TAILINGS POND
MILL
LEACH
CCD
PRODUCT RECOVERY
STORAGE
OFFICE
SCALE HOUSE
ENTRANCE
WATER STORAGE TANKS
EMERGENCY TAILINGS POND
MOLY STORAGE
TOPSOIL
DRAINAGE COLLECTION AREA
DRAINAGE COLLECTION AREA
DRAINAGE COLLECTION AREA
COUNTY ROAD
Scale 0 100 200 300 Meters
Axis of tailings dam
60
El 112 8 Maximum level of tailings
El 114 3
Shell
3 0
1
1
1
Central core
1
1
2 0
1
Material excavated from pond area for use in dam
Tailings
Varies
"A" sand
"A" sand
1
1
1
1
0 6 Min
Silt - clay layer
Scale 0 5 10 20 30 Meters

Figure 3-11. Diagram of Chevron's Panna Maria mill site and a cross-section through the tailings dam.

The tailings discharge to the impoundment is periodically moved around the perimeter of the pile. An exposed beach of coarse tailings forms along the dike with tailings solution in the center portion of the pond. The depth of the solution varies from a 1.5-m (5-ft) average on the east side to 5 to 6 m (15 to 20 ft) on the west (Ma85). Later this year when the mill is on standby, the tailings solution will be neutralized with calcium carbonate (mine overburden).

The radon-222 flux from the tailings has not been measured. Radon-222 measured on the dike of the tailings pile is less than 0.5 pCi/liter (Ma85). No measurement of radium-226 content of the tailings was available.

The ore pad at this facility covers approximately 30 acres. During normal operations, a 1-month supply of ore [69,000 t at capacity] is stockpiled on the pad.

A 1983 survey of population in the area indicated that 453 people live within 5 km (3.1 mi.) of the tailings pile, 12 people live within 1 km (0.6 mile) of the tailings pile, 42 live between 1 and 2 km (0.6 and 1.25 mi.) of the tailings pile, and 33 live between 2 and 3 km (1.25 and 1.9 mi.) from the tailings pile (EPA83b).

The average annual rainfall at the location of the pile is 30 inches, and the net annual evaporation is 35 inches (Br80).

### Conquista Mill

The Conquista Mill, a joint venture of Continental Oil (operator) and Pioneer Nuclear, is located near Falls City, Texas, about 48 km (30 miles) southeast of San Antonio. The topography is relatively flat. This mill was shut down in May 1981; however, waste solids from ongoing in situ mining are being disposed of in the Conquista tailings pile. The mill, which began operation in 1972, had a production capacity of 3200 t of ore per day. When this mill was in operation, this production capacity included about 500 t per day of toll-processed ore from Exxon Minerals' Felder open-pit mine in Live Oak County.

When in operation, this mill recycled nearly all of the water sent to the main tailings pile--less the amount evaporated and the amount entrained with the solid tailings. Tailings slurry and SX raffinate bleed were pumped to the single tailings pile. Provisions have been made to collect any seepage. No seepage has been detected, however, which can be attributed to the underlying bentonitic clay and natural shale.

One side of the tailings pile has been keyed into the side of a hill. Dikes have been built around the other three sides of the pile. The embankment consists of clays and earthen materials. If the plant becomes active, the mill operators expect to raise the dikes by 6 m (20 ft). The tailings pile currently stores 5.6 x $10^6$ t of solids.

The total area covered by tailings in the pile is 250 acres (Ch85). The average depth of tailings is 7.5 m (25 ft), ranging from 5 to 16 m (15 to 55 ft). Currently, 50 acres are covered by 175 x $10^6$ gallons of tailings solution that ranges in depth from less than 0.3 to 7 m (1 to 22 ft) (Ch85). Approximately 80 acres of this pile have been covered with a layer of soil material up to 1.5 m (5 ft) thick to allow access to the pile by heavy machinery. There are approximately 70 acres of exposed sand tailings and 50 acres of exposed slimes. Of this total, some 70 acres remain saturated (Ch85). Additionally, 50 acres of the exposed tailings are currently sprayed and wetted for dust control and enhanced evaporation.

The radium-226 content averages 114 pCi/liter in the tailings solution (Ch85). Radon-222 flux measurements were taken in 1983 and 1984 and averaged 23 $pCi/m^2$-s with a range of 0.1 to 65 $pCi/m^2$-s (Ch85). Ambient radon-222 concentrations at locations around the pond are reported to be well below maximum allowable concentrations (Ch85).

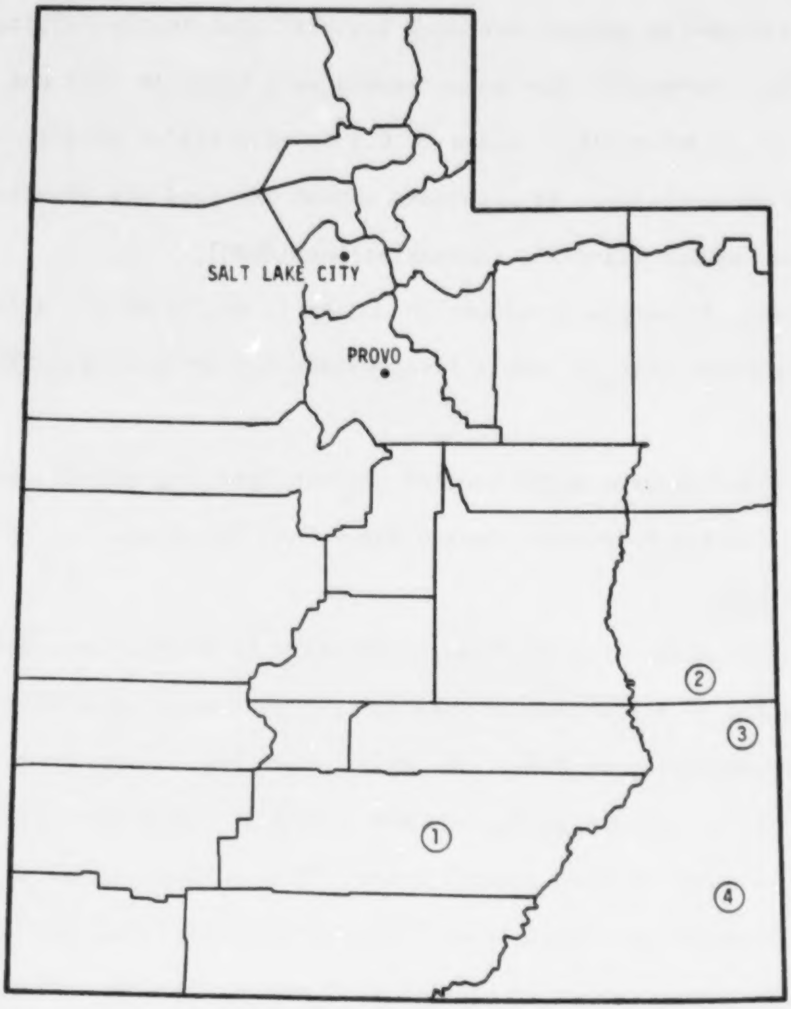
In 1980, 33 people lived within 3.2 km (2 mi.) (Ch85). A 1983 survey indicated that 42 people lived within 5.0 km (3.1 mi.) (EPA83b).

### 3.3.5 Utah

The four licensed mills located in Utah (see Figure 3-12) are owned by Atlas, Plateau Resources, Energy Fuels, and Rio Algom.

#### Moab Mill

The Moab Mill owned by Atlas Corporation is located in a long, narrow valley of a mountainous area in Utah on the Colorado River about 5 km (3 mi.) northwest of Moab. The mill, which began operations in October 1956, is on standby status and not currently operating. The milling process has been modified several times. The milling process originally used involved sulfuric acid leach resin-in-pulp (RIP) followed by nitrate elution and precipitation of uranium with ammonia (DOE80). The mill was converted to an alkaline-leach RIP process in 1961 (DOE82). An acid leach solvent extraction process was installed in 1967. Shortly thereafter, the RIP operation was abandoned. The combined acid and alkaline circuits give the Moab mill greater flexibility in handling a variety of ores (DOE82). Grinding is by a dry rod mill (NRC84). Ore is hauled an average distance of about 30 km (50 mi.) by truck. Uranium is produced for sale to the AEC and commercial buyers. Capacity of the mill is about 1800 t of ore per day (NRC84).


SALT LAKE CITY
PROVO
①
②
③
④

1. Plateau Resources, Ltd.
   Shootaring Canyon Mill
2. Atlas Minerals
   Moab Mill
3. Rio Algom Corp.
   La Sal Mill
4. Union Carbide
   White Mesa Mill

Figure 3-12. Location of mills in Utah.

Prior to 1977, mill tailings were discharged to the Colorado River (NRC84). Since that time, all tailings have been impounded in a single tailings pile. The pile is constructed with earthen dikes. Tailings are discharged from multiple spigots around the periphery of the dike. The coarse sand is deposited on and near the dike, while the fines are carried to the interior of the pond with the tailings solution. About 125 acres are covered with tailings to a depth of nearly 24 m (80 ft); the top surface of the pile covers about 80 acres (DOE82). Because the embankment is on a sloping surface, its height varies from 6 to about 36 m (20 to about 120 ft) above ground (DOE82) (see Figure 3-12). Between 7 and 9 x $10^6$ t of tailings are contained in this pile (DOE82, NRC84). A diagram of the site is presented in Figure 3-13.

The radium-226 content of tailings has been reported to be 540 pCi/gram (EPA83). Ore grade ranges from 0.20 to 0.25 percent $U_3O_8$, and the extraction efficiency is 94 to 96 percent (NRC84).

Moab is the only nearby incorporated community. In 1980, the total estimated population within a 16-km (10-mi.) radius of the mill was 6300 people (DOE82). The closest resident is reported to live 2 km (1.25 mi.) away (DOE82). A 1983 survey indicated a population of 2361 within a 5-km (3.1-mi.) radius of the tailings pile (EPA83b). The same survey indicated 42 people living within 3 km (1.9 mi.).

The climate at the site is semiarid and has an annual precipitation of 8 inches and an annual evaporation rate of 64 inches (EPA83). Because of the drying effect, the tailings are sometimes wetted with sprinklers and/or a chemical dust suppressant such as Coherex to minimize dusting (DOE82). Wind speeds usually are quite low (DOE82).

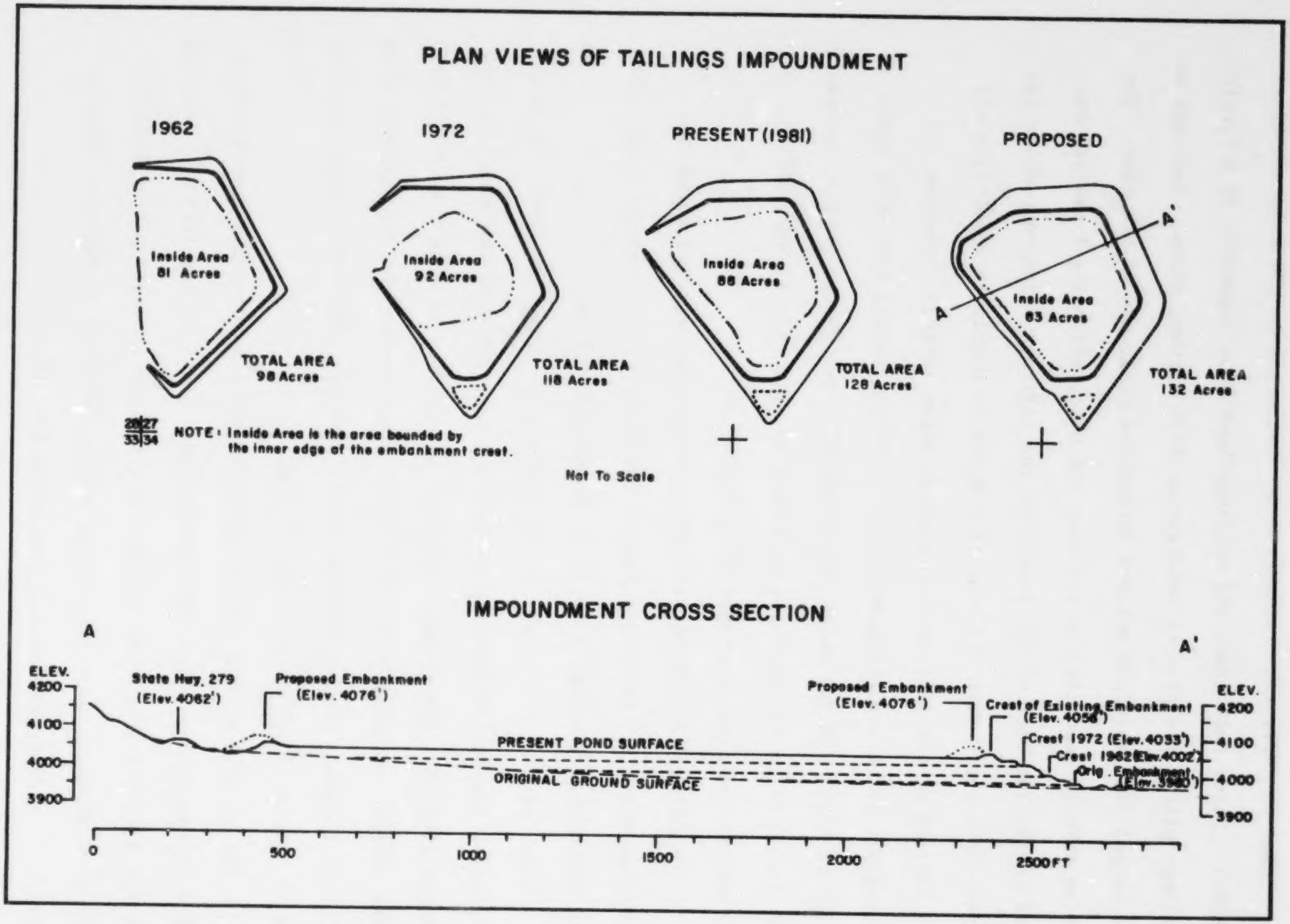

PLAN VIEWS OF TAILINGS IMPOUNDMENT
1962
1972
PRESENT (1981)
PROPOSED
Inside Area 81 Acres
TOTAL AREA 98 Acres
Inside Area 92 Acres
TOTAL AREA 118 Acres
Inside Area 88 Acres
TOTAL AREA 128 Acres
Inside Area 83 Acres
TOTAL AREA 132 Acres
A
A'
28|27
33|34
NOTE: Inside Area is the area bounded by the inner edge of the embankment crest.
Not To Scale
IMPOUNDMENT CROSS SECTION
A
A'
ELEV.
4200
4100
4000
3900
State Hwy. 279 (Elev. 4062')
Proposed Embankment (Elev. 4076')
PRESENT POND SURFACE
ORIGINAL GROUND SURFACE
Proposed Embankment (Elev. 4076')
Crest of Existing Embankment (Elev. 4056')
Crest 1972 (Elev. 4033')
Crest 1962 (Elev. 4002')
Orig. Embankment (Elev. 3980')
0
500
1000
1500
2000
2500 FT

Figure 3-13. Configuration of the tailings pile at the Moab mill.

### Shootaring Canyon Mill

Plateau Resources, Ltd., owns the Shootaring Canyon Mill, which was operational only from April to October 1982. The capacity of the mill is 725 t per day. The average ore grade is 0.15 percent $U_3O_8$, ranging from 0.07 to 0.24 percent. An average of approximately 88,000 t of surface mined ore is stockpiled on site, when the mill is running at capacity. The primary mill circuit involves semi-autogenous grinding of the sandstone ores followed by a sulfuric acid leach. All generated tailings are discharged to an onsite tailings pile. The tailings disposal system is a planned, staged disposal process. An earthen dam has been constructed across the valley. Behind the earthen dam, birms have been constructed to form five cells for tailings disposal. Because of the short period of operation, only one cell contains a significant quantity of tailings. Two other cells contain only minor quantities, and the other two cells contain none. Less than 10 acres are covered by tailings, and about 3 of these acres are covered with water (Ge85). Plateau Resources has taken steps to temporarily stabilize this pile by inducing water evaporation and placing a 0.3-m (1-ft) cover of local soil over the tailings to limit windblown dust. This interim stabilization process will be completed in approximately 3 years. Radon-222 flux from the tailings has not been measured. A site map or diagram was not available for inclusion in this report.

The area around the mill is sparsely populated with no inhabitants living within a 3-km (2-mi.) radius (EPA83b).

### White Mesa Mill

Energy Fuel's White Mesa mill, which is about 8 km (5 mi.) south of Blanding, Utah, began operating in July 1980. The mill currently is on standby status. Semi-autogenous grinding, acid-leaching, and solvent-extraction are used to process ores containing about 0.13 percent $U_3O_8$; about 730 t of $U_3O_8$ are recovered annually (NRC84).

Tailings were originally generated at a rate of about 1800 t of solids per day (NRC84). Approximately 500,000 t of tailings are contained in two below-grade cells of a proposed six-cell disposal system. Each of the cells covers about 40 acres. The proposed system was to feature simultaneous construction, operation, closure, and reclamation. An alternative approach of constructing a larger above-grade pile may be pursued if and when the plant reopens. The tailings are reported to contain 350 pCi/g of radium-226 (EPA83b). A site map was not available.

A 1983 population survey indicated that no inhabitants live within a 4-km (2.5-mi.) radius of the tailings pile. The same survey counted 8 persons living between 4 and 5 km (2.5 and 3.1 mi.) from the tailings disposal area.

### Lisbon Mill

The Lisbon mill owned by Rio Algom is about 48 km (30 mi.) southeast of Moab, Utah. This active mill has been in operation since 1971. Ore obtained from adjacent underground mining operations is processed by alkaline leaching and ion exchange. The mill's designed throughput is 670 t of ore per day.

Over $1.6 \times 10^6$ t of tailings have been generated at this mill. The tailings are contained in two unlined tailings piles retained by natural soil embankments placed across a drainage course, one immediately upstream of the other (NRC84). The lower pile has been in use since 1971, the upper since 1976. The total area of the tailings is about 35 acres. The tailings are reported to contain 560 pCi/g of radium-226 (EPA83b). A site map or diagram was not available.

A 1983 survey of the population in the area indicated that no inhabitants live within 0.5 km (0.3 mi.) of the tailings pile (EPA83b). Eight inhabitants were reported to live between 0.5 and 1.0 km (0.3 and 0.6 mi.) from the pile, and 105 between 1 and 2 km (0.6 and 1.2 mi.) from the pile.

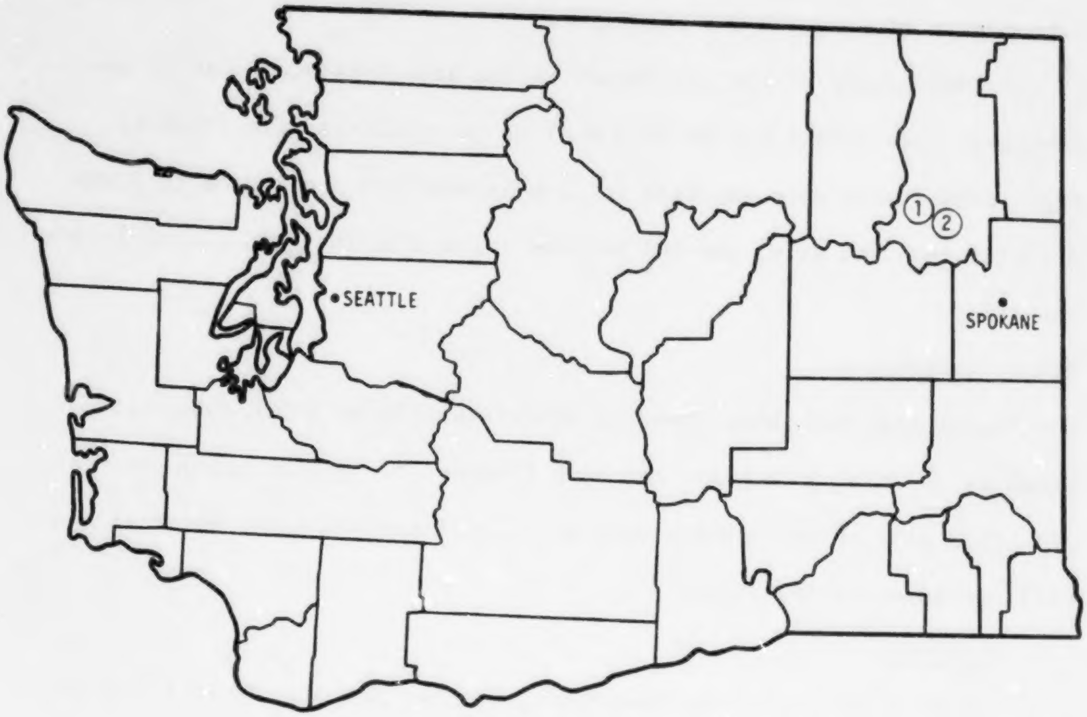
### 3.3.6 Washington

Washington has three licensed mills (see Figure 3-14). One mill, owned by Joy Mining Company, has been licensed but is not yet operational. This mill is not conventional as it will process a bog material and will not generate tailings.

#### Ford Mill

The Ford Mill owned by Dawn Mining Company is about 72 km (45 mi.) northwest of Spokane, Washington. The mill is jointly owned by Newmont Mining Corporation and Midnight Mines, Inc. It began operations in 1957 and operated through 1964 under the AEC concentrate purchase program. The mill was shut down and rehabilitated between 1965 and 1969. As of December 1984, the mill was inactive and on standby status.

The production capacity of the mill is 550 t of ore per day. The mill circuit incorporates a two-stage agitation acid leach process followed by ion exchange and precipitation of uranium with ammonia. The Midnight open-pit mine produces ore between 0.10 and 0.25 percent $U_3O_8$ (NRC84). The usual practice is to maintain a 1-year supply of ore (193,000 t) on a 14-acre stockpile at the mill site (DOE82). Radon-222 would be emitted from this stockpile and from the crushing and grinding circuit when the mill is operational.


SEATTLE
SPOKANE
①
②

1. Dawn Mining Co.
   Ford Mill

2. Western Nuclear, Inc.
   Sherwood Mill

Figure 3-14. Location of mills in Washington.

The tailings generated by the Ford Mill are contained in four separate piles (see Figure 3-15). Three of these piles are above grade, unlined, and constructed behind earthen dams. These three piles have been filled to capacity and are inactive. Piles 1 and 2 cover about 65 acres and contain an estimated 1.06 x $10^6$ t of tailings from AEC contract production. They have been covered with about 0.61 m (2 ft) of sandy soil and wood chips for dust control and interim stabilization (DOE82, An84). Pile 3 covers 46 acres and has also been covered with sandy soil and wood chips. Impoundment 4 is an excavated, below-grade, lined (Hypalon) pond covering 28 acres. There is no exposed beach area in this pond (An84). The tailings are covered with water 1.2 to 1.5 m (4 to 5 ft) deep. Radon-222, which emanates from the three inactive ponds that cover 111 acres, is probably reduced about 30 percent by the interim stabilization cover (EPA83). The below-grade pond is not a major source of radon-222 because of its deep water cover. The radium-226 content of the Ford Mill tailings is reported to be 850 pCi/g (EPA83b).

The small community of Ford is located within 3.2 km (2 mi.) of the tailings piles. In 1983 approximately 411 people were living within 5 km (3.1 mi.) of the tailings piles (EPA83). The nearest resident is reported to live about 640 m (700 yards) from the mill (DOE82).

The area's topography is characterized by rolling hills. The average annual precipitation is 12 to 18 inches; annual evaporation is about 50 inches (EPA83b).

### Sherwood Mill

Western Nuclear's Sherwood uranium mill, which is operated by Western Nuclear, Inc., is located in eastern Washington State about 64 km (40 mi.) northwest of Spokane, Washington. The land surface at the mill

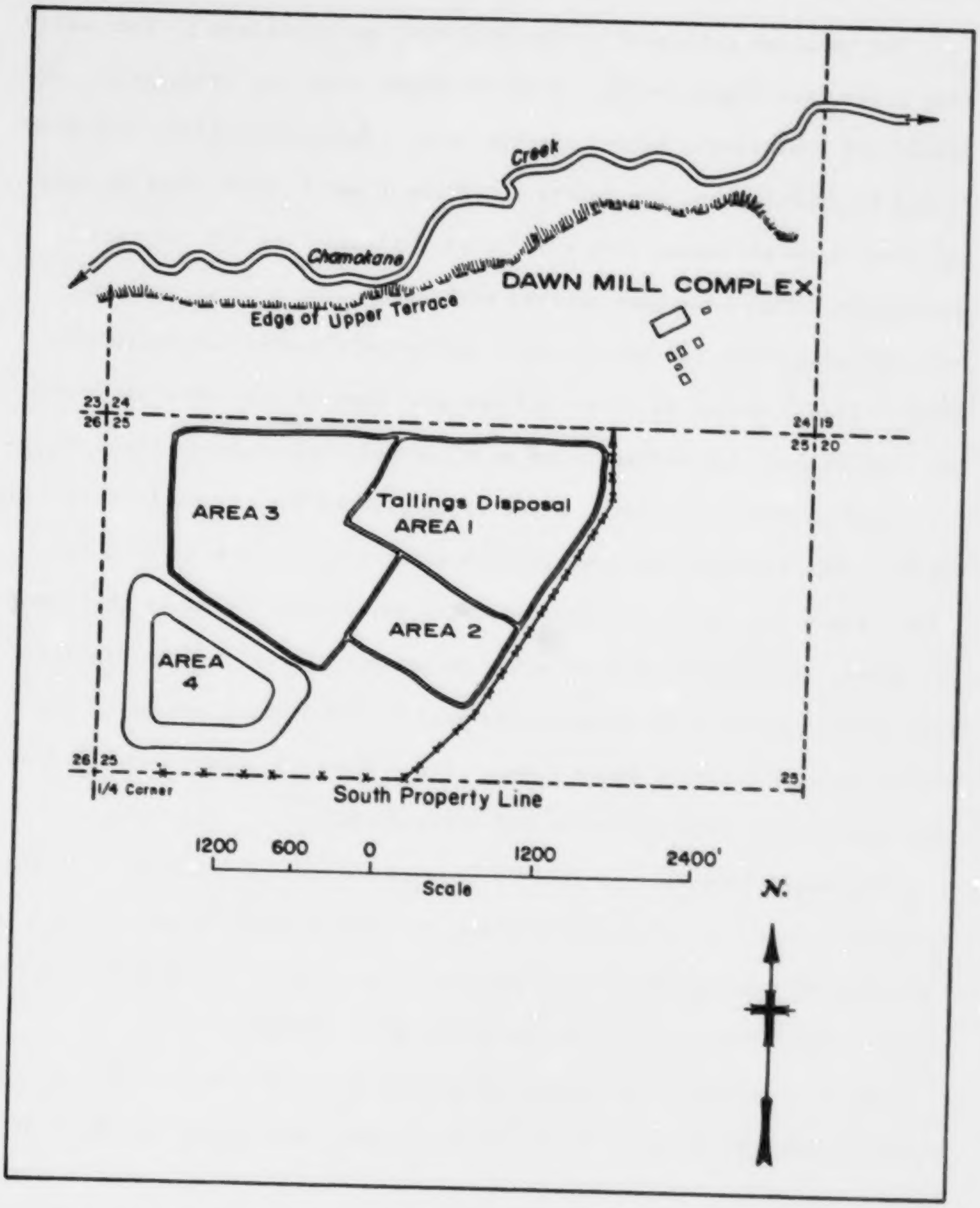

Chamokane
Creek
Edge of Upper Terrace
DAWN MILL COMPLEX
23 24
26 25
24 19
25 20
AREA 3
Tailings Disposal
AREA 1
AREA 2
AREA 4
26 25
1/4 Corner
South Property Line
25
1200
600
0
1200
2400'
Scale
N.

Figure 3-15. Diagram of the Dawn Mill and associated tailings piles.

Note: Tailings Areas 1, 2, and 3 are above-grade piles that have been filled to capacity. Area 4 is a lined, below-grade impoundment.

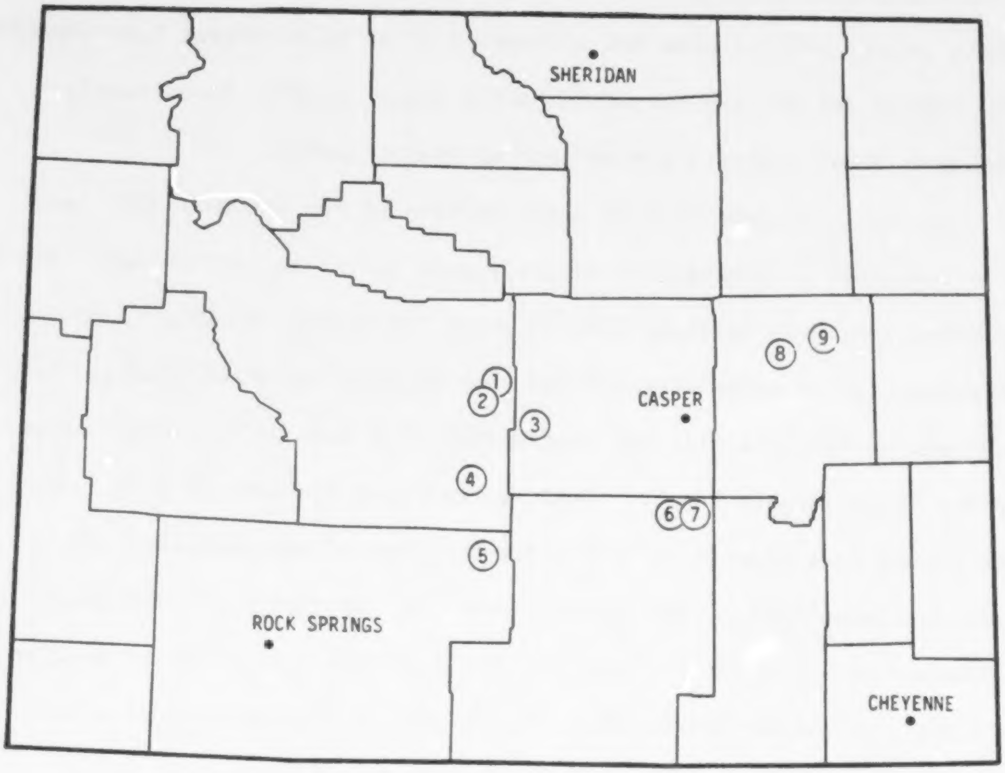
is mostly gently sloping and relatively smooth and uniform. Ore taken from a nearby surface mine has averaged 0.05 to 0.09 percent $U_3O_8$ (EPA83). This mining and milling operation, which began in 1978, is currently (December 1984) inactive and on standby status (An84).

The tailings generated by acid leaching at the Sherwood Mill have been impounded in a single above-grade pile behind an earthen dam. As of December 1984, the tailings covered about 135 acres. Of this total, approximately 60 acres were covered with tailings solution (An84). Tailings slurry from the mill was neutralized with lime before it was pumped to the lined (Hypalon) pile. Tailings solution decanted from the pile was pumped to a 25-acre evaporation pond situated upstream from the tailings impoundment. The current amount of tailings under management is estimated at $1.5 \times 10^6$ t (NRC84). The tailings are reported to contain 200 pCi/g of radium-226 (EPA83). A site map or diagram was not available.

The area is very sparsely populated. One permanently occupied ranch and one intermittently occupied ranch are the only dwellings within 3.2 km (2 mi.) (An84). A 1983 survey reported 49 people living within 5 km (3.1 mi.). Annual precipitation is 10 to 15 inches, and annual evaporation is about 50 inches (EPA83b).

### 3.3.7 Wyoming

Nine mills are located in Wyoming (see Figure 3-16). One of these mills is decommissioning, three are active, and five are on standby status.


SHERIDAN
CASPER
ROCK SPRINGS
CHEYENNE
1
2
3
4
5
6
7
8
9

1. American Nuclear Corp.
   Gas Hills Mill
2. Pathfinder Mines Corp.
   Gas Hills Mill
3. Union Carbide
   East Gas Hills Mill
4. Western Nuclear, Inc.
   Split Rock Mill
5. Minerals Exploration Co.
   Sweetwater Mill
6. Pathfinder Mines Corp.
   Shirley Basin Mill
7. Petrotomics
   Shirley Basin Mill
8. Rocky Mountain Energy
   Bear Creek Mill
9. Exxon Corp.
   Highland Mill

Figure 3-16. Location of mills in Wyoming.

## Shirley Basin Mill

The Petrotomics Mill, currently owned by Texaco, is located about 77 km (48 mi.) southeast of Casper, Wyoming, in the eastern Shirley Basin area of Wyoming. The mill, which began operation in 1962, is currently active and processing ore at a rate of 730 t per day; capacity is 1360 t per day (Pa85). The ore, which is a coarse sand material, is mined by surface mining methods. A 3-month supply (136,000 t) of the mine run ore is usually stockpiled on a 40-acre pad; currently, 91,000 t are in storage (Pa85). The mining operation depleted the ore body in February 1985, but stockpiled ore will allow processing operations to continue through May 1985. An additional 455,000 t of low-grade ore have been stockpiled, but will probably not be processed. Although other mining operations have been planned, they have not been developed. The mill will be inactive for at least 2 years (the time required to develop a new mine) and possibly permanently. While the mill is inactive, no ore will be stockpiled on the pad.

All tailings from the Petrotomics Mill are sent to a single tailings pile. Approximately $6.2 \times 10^6$ t of tailings have been produced, including tailings generated under government contract, which are commingled with commercial tailings (DOE82). The tailings are disposed of above grade behind a horseshoe-shaped clay dam. The total area covered by tailings in January 1985 was 140 acres (Pa85). Tailings are spigotted from the dam and solids settle out and form a beach area with the tailings solution ponded in the interior portion of the pile. Tailings solution currently covers an estimated 40 to 50 percent (56 to 70 acres) of the total pile area (Pa85). The exposed beach area covers 70 to 84 acres. Petrotomics has determined that the radium-226 content of the mill run tailings (both sands and slimes) is approximately 558 pCi/g (Pa85). Radium-226 content ranges from 180 to 700 pCi/g, depending on size fractions. A representative from Petrotomics stated that the 558-pCi/g figure is the best average to use for the radium-226 content in the beach area. After operations cease, the exposed beach area will gradually increase as the tailings solution evaporates. The pile will not be stabilized or closed until a final decision is made on whether to open another mine or to close the facility entirely. A diagram or site map was not available.

The area around the Petrotomics Mill is sparsely populated. A 1983 survey reported 357 people living within a 5-km (3.1 mi.) radius of the tailings pile (EPA83). The annual precipitation in the area averages 12 inches, while evaporation is about 43 inches (EPA83b).

### Sweetwater Mill

The Sweetwater Mill of Minerals Exploration Company is located within the Red Desert portion of Wyoming's Great Divide Basin, about 64 km (40 mi.) northwest of Rawlins. The mill, which began operations in early 1981, has been inactive since May 1983 and is on standby status. The capacity of the mill is 2700 t per day. The average ore grade processed to date has been 0.03 percent $U_3O_8$ (Hi85).

All tailings have been placed in a single tailings pond. The pond is partially below grade with earthen embankments. The total area of the tailings is 40 to 45 acres. With the exception of a 1- to 2-acre delta at the tailings discharge point, the pond is covered by tailings solution. Approximately $0.9 \times 10^6$ t of tailings have been generated and are contained in this pile. The Minerals Exploration Company reports that measurements of radon-222 flux made on the tailings solids ranged from 90 to 100 pCi/m$^2$-s (Hi85). When operations resume, tailings will be placed in this pile as additional capacity becomes available. Plans call for a second cell to be constructed to the north of the existing cell if additional capacity is required. The Sweetwater tailings disposal system is a staged facility that has gone through several iterations during development. The pile was originally designed to include a square below-grade pile divided into four cells. A site map or diagram was not available.

A 1983 survey indicated no population living within 5 km (3.1 mi.) of the tailings pile (EPA83). The annual precipitation in the area is 6 to 8 inches, while annual evaporation is 40 to 70 inches (EPA83).

### Bear Creek Mill

Rocky Mountain Energy's Bear Creek Mill is part of a uranium project that includes open-pit mining operations in Converse County, Wyoming, about 72 km (45 miles) northeast of Casper. The operation, which was dedicated in September 1977, is currently active with a capacity of 1800 t of ore per day (NRC84). The $U_3O_8$ content of the ore ranges from less than 0.1 to 1.0 percent (NRC84). Ore is stockpiled at the mill on a 20-acre ore pad; approximately 60,000 t are currently on hand (Me85).

Mill tailings are contained in a single tailings impoundment enclosed by an earthen dam. The tailings cover about 120 acres, of which 20 to 30 acres are covered with tailings solution and 20 acres are exposed tailings beaches (Me85). The remainder of the pile is covered with 1 foot of clay that has been put in place to control fugitive dust (Me85).

A map of the site showing the configuration of the pile and its orientation to the mill is shown in Figure 3-17.

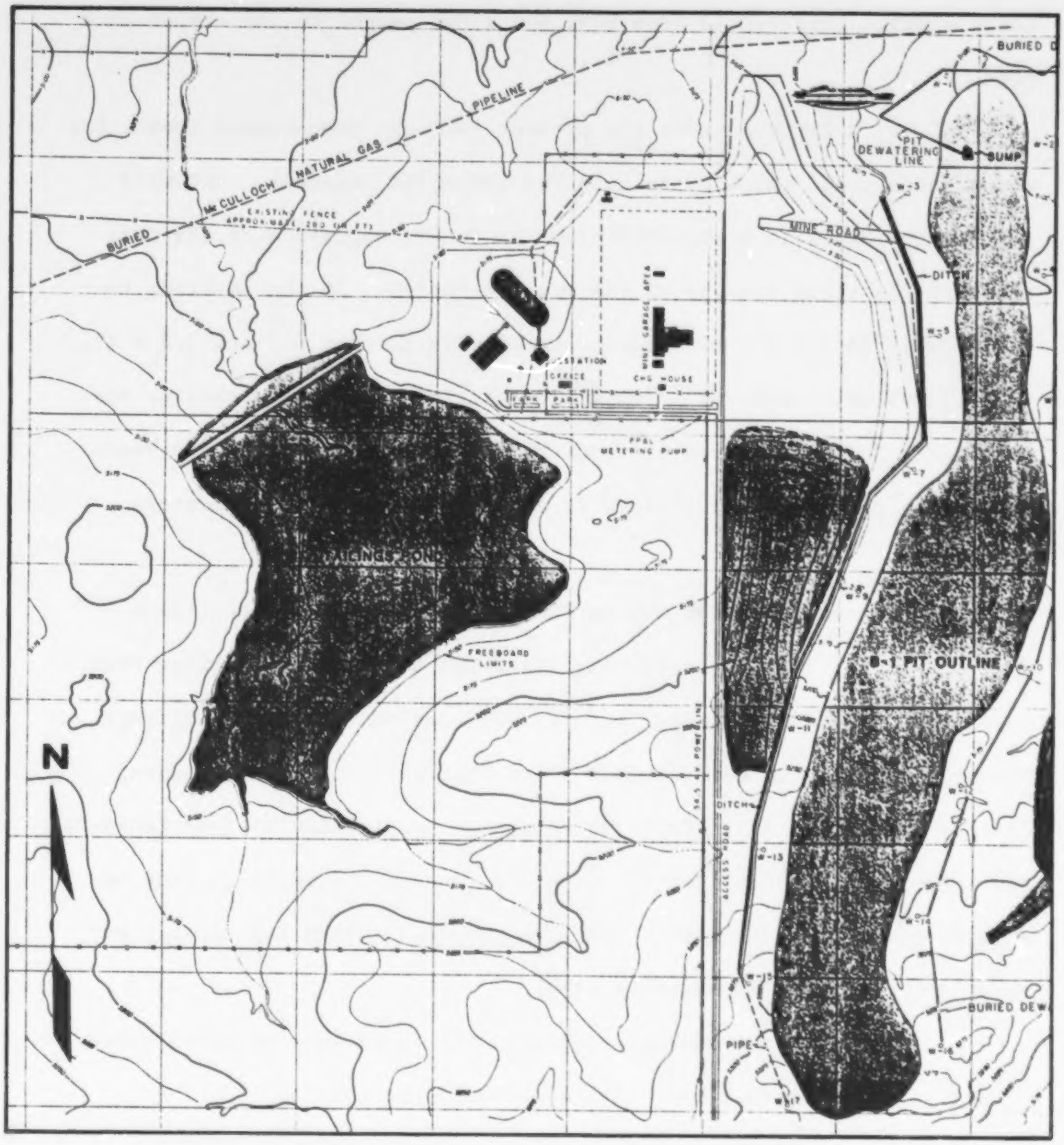
No measurements of radon-222 flux from tailings have been made at this site. The radium-226 content of the Bear Creek tailings is reported to be 420 pCi/g (EPA83b). A representative of the company believes this value is too high, but no other measurements were available (Me85).

A 1983 survey indicated that no one lives within a 5-km (3.1 mi.) radius of the tailings pile (EPA83b). The annual precipitation in the area is about 12 inches, while annual evaporation is 40 inches (EPA83).

## Gas Hills Mill

The Gas Hills Mill of the American Nuclear Corporation (ANC) is in a hilly area of Wyoming, about 80 km (50 mi.) east of Riverton. The mill began operation in October 1959 with an initial rated capacity of 470 t of ore per day. The mill, which has been inactive since October 1981, is now licensed for a capacity of 860 t per day. Dry grinding, acid leach, and the Eluex process are used at the mill; ion exchange is carried out in a resin-in-pulp circuit. The ANC mill is currently decommissioning.

Mill tailings were pumped to two conventional above-ground piles formed by peripheral earth dams. Pile No. 1 covers approximately 38 acres and contains tailings generated under AEC contracts (DOE82). This pile has also recently served as an evaporation pond. Pile No. 2 covers about 78 acres and contains commingled (AEC and commercial contract) tailings (DOE82). This pile is contained by a three-sided earthen embankment. The upstream embankment, the fourth side of the pile, was made of sand tailings. Approximately $5.9 \times 10^6$ t of tailings are contained in


BURIED McCULLOCH NATURAL GAS PIPELINE
EXISTING FENCE
APPROXIMATE, 280 (IN FT)
BURIED D
PIT DEWATERING LINE
SUMP
MINE ROAD
DITCH
MINE GARAGE AREA
SUBSTATION
OFFICE
CHG HOUSE
PARK
PARK
PPSL METERING PUMP
TAILINGS POND
FREEBOARD LIMITS
34.5 KV POWERLINE
ACCESS ROAD
DITCH
B-1 PIT OUTLINE
BURIED DEW
PIPE
N
W-1
W-2
W-3
W-5
W-7
W-9
W-10
W-11
W-13
W-14
W-15
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W-17

Figure 3-17. Diagram of the Bear Creek mill site, tailings pile and one of the mine pits.

these piles. Free liquid from Pond No. 2 was pumped to the evaporation pond.

ANC has determined that the present tailings impoundment system has enough additional capacity to hold the estimated reserves. ANC will present the NRC with a proposed plan for future operation of the mill which will include the use of the present system. In the interim, the tailings in Pond No. 2 have been covered with between 0.2 and 1.2 m (0.5 to 4 ft) of spoil material from an adjacent mine dump to stabilize the tailings. No measurements of radon-222 flux from the piles have been made. The tailings are reported to contain 420 pCi/g of radium-226 (EPA83b).

Interim stabilization and reclamation of the existing tailings disposal system involves rerouting the draws adjacent to Tailings Pond No. 2 to convey surface water runoff away from the reclaimed tailings. The tailings will be covered to a level that will ease erosion when finally reclaimed and control the release of radioactivity from radon-222 gas to a level of 20 $pCi/m^2$-s. Stabilization of the tailings pond has already been completed with a contaminated soil survey and cleanup and rerouting of the Willow Springs Draw.

A 1983 population survey indicated that there were no inhabitants living within 5 km (3.1 mi.) of the ANC tailings pile (EPA83b).

No map or site diagram was available for inclusion in this report.

### East Gas Hills Mill

The East Gas Hills Mill is part of the Union Carbide Uranium Project in the southeastern portion of the Wind River Basin of Wyoming. The mill is about 95 km (60 mi.) west of Casper in an area of rolling hills interspersed with relatively flat areas.

An acid-leach system (RIP-Eluex system) is used to recover uranium. Recycled solution from the impoundment system is used to wash sands after sand-slime separation. Additional pond decant solution is used for tailings dilution. The mill began operation in early 1960 with a capacity of about 1000 t per day; in January 1980, the capacity was increased to 1300 t per day. In June 1983, milling of mined ore was temporarily curtailed, with only the heap leach facility kept in operation. No information is available on the output of this facility. Ore is sufficient to maintain the current milling rate for 5 to 10 more years. During milling operations, a 2-month stockpile of ore is maintained at the mill (Wo85). This amounts to 78,000 t when the mill is operating at capacity.

During the anticipated total active life of the project (1960 to 1986), about 12 x $10^6$ t of mill tailings will have been produced. The retention capacity (7.6 x $10^6$ t) of the mill's original above-grade tailings impoundment has been reached, and since January 1980, tailings have been discharged to a depleted open-pit mine (Pit A-9) with a capacity of 2.3 x $10^6$ t. The pit, designated the A-9 pit, has an area of 26 acres, is clay-lined on the bottom, and has an in-pit dewatering system. Pit A-9 has an exposed tailings beach area of about 12 to 15 acres (Wo85). The evaporation area consists of two ponds with a combined surface area of 24 acres. The maximum height of the embankment of the original above-grade tailings pile (and expansions) is about 14 m (45 ft). This pile covers 160 acres and contains 5.8 x $10^6$ t (6.4 x $10^6$ ST) of comingled tailings (Wo85). The inactive tailings area, which has not been used since January 1980, is presently in a preliminary phase of reclamation. The inactive pile has been covered with an average thickness of 1.2 m (4 feet) of overburden (Wo85). The tailings are reported to contain 310 pCi/g of radium-226 (EPA83b). A site diagram is presented in Figure 3-18.

An EPA report estimates the radium-226 content of the tailings to be 310 pCi/g (EPA83b). No measurements of radon-222 flux from the tailings pile have been made at this site (Wo85).

The area is sparsely populated. A 1983 survey indicated no human population living within a 5-km radius of the tailings pile (EPA83b). Average annual precipitation is 10 inches while evaporation is 42 inches (EPA83b).

Under the present reclamation plan, Union Carbide is committed to provide a uniform cover of 0.3 m (1 ft) of clay and 2.6 m (8.5 ft) of overburden over the entire tailings area. This will require about 210,000 $m^3$ ($7.5 \times 10^6$ $ft^3$) of clay costing \$1,129,000 and $1.8 \times 10^6$ $m^3$ ($65 \times 10^6$ $ft^3$) of overburden costing \$1,840,000 (NRC84). When the cost of revegetation is added, the basic materials needed for the reclamation program will cost about \$3,800,000. Union Carbide has also provided a general plan for the decommissioning of the mill structures and will submit a detailed plan prior to termination of the milling operation. Union Carbide is committed to maintaining a surety bond with the State of Wyoming to cover reclamation and mill-decommissioning costs.

Union Carbide also operates a heap leach facility in the mill area at its East Gas Hill site. The water used in the process [1.7 liters/s (27 gal/min)] is taken from a nearby tailings area, and $U_3O_8$ is recovered

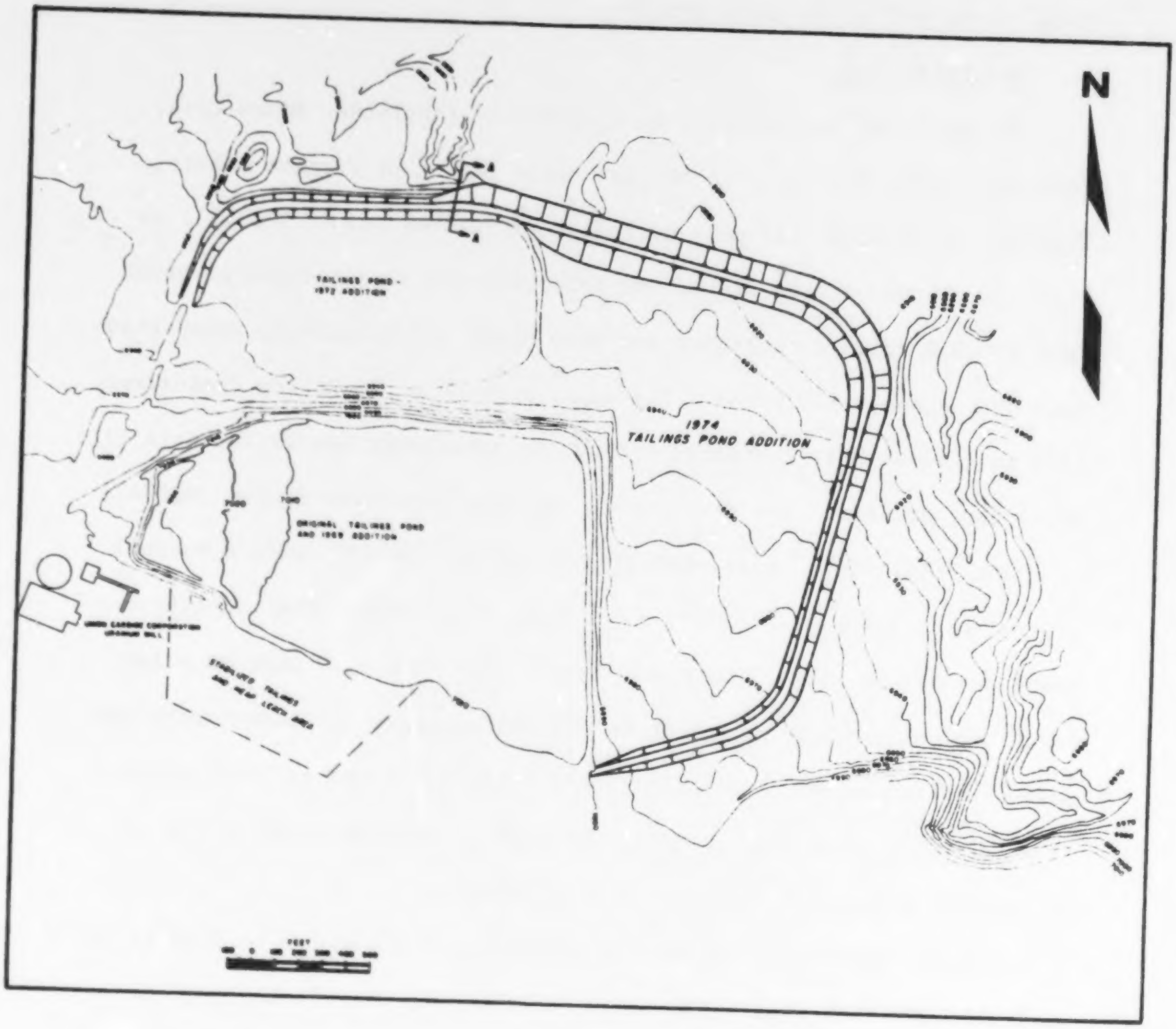
N
TAILINGS POND - 1972 ADDITION
1974 TAILINGS POND ADDITION
ORIGINAL TAILINGS POND AND 1969 ADDITION
UNION CARBIDE CORPORATION URANIUM MILL
STABILIZED TAILINGS AND HEAP LEACH AREA
A
A
FEET

Figure 3-18. Orientation of the tailings pile and mill at Union Carbide's Gas Hills mill.

from high-grade leach liquor by a solvent-extraction process. The organic phase is pumped to the mill circuit.

### Gas Hills Mill

The Lucky Mc Uranium Mill is operated by Pathfinder Mines Corp. (formerly Lucky Mc Corp.) in the Gas Hills region of Fremont County, Wyoming, about 40 km (25 mi.) northeast of Jeffrey City. The mill is near the divide between Fraser and Reid Draws at an elevation of about 2000 m (6540 ft). Both Fraser and Reid Draws are relatively steep-gradient drainageways (19 m/km). The upper portion of Reid Draw drainageway [342 ha (845 ac)] is contained behind the embankment dam of Tailings Pile No. 4 and serves as part of the mill tailings retention system (NRC84).

This mill first began producing yellowcake in 1958 with a nominal ore-processing capacity of 850 t per day. Since then, the capacity has been expanded to about 2500 t of ore per day. The mill uses an acid-leach process and was the first in the United States to incorporate the moving-bed ion-exchange technique originally developed in South Africa. It is also the only U.S. uranium mill that uses anion exchange for concentration of uranium from the feed solution.

Company-owned open-pit mining operations located 1.5 to 3 km (1 to 2 mi.) from the mill supply 90 percent of the ore; the remaining 10 percent is produced at Pathfinder's Big Eagle Mine near Jeffrey City. The ore grade has averaged 0.21 percent $U_3O_8$ in past operations and is expected to average 0.11 percent in the future (Ha85). Although mines adjacent to the mill also could provide fresh water for ore processing, the availability of hot [57°C (135°F)] well water at the site makes it advantageous from a process standpoint to use well water in the mill and to treat mine water for discharge.

The tailings retention system consists of five tailings piles encompassing about 320 acres (Ha85). The ponds are situated sequentially in the head of Reid Draw north-northeast of the mill and are dug into an underlying shale formation. Clay core dams keyed into the shale provide protection against lateral seepage. Only three of the five tailings piles now contain tailings. The total tailings area of these three piles is about 160 acres (Ha85). The average tailings depth is now 12 m (40 ft) and is expected to increase to 18 m (60 ft) by the end of the projected milling operation in 1996 (Ha85). The remaining two piles are now used for solution evaporation. Water is sprayed over 19 acres of the dry tailings during warm weather to control dust (Ha85). Dry beaches are limited to 20 acres by maintaining the fluid level in the pond (Ha85). The current amount of tailings under management is 10.5 x $10^6$ t (Ha85). A site map or diagram was not available.

Radon-222 flux has not been directly measured from the tailings at the Lucky Mc Mill. The radium-226 activity for the solid tailings, combined sands, and slimes is about 160 pCi/g (Ha85). An earlier EPA report estimated the radium-226 content at 420 pCi/g (EPA83b). The radium-226 activity of the tailings liquid is approximately 200 pCi/liter (Ha85).

The Lucky Mc Mill is in a remote location away from permanent habitation. The nearest residence is approximately 19 km (12 mi.) away (Ha85). A 1983 survey also indicates no population within a 5-km radius of the tailings piles (EPA83b).

A 1963 flood at the mill site resulted in the release of 8.7 x $10^7$ liters (2.3 x $10^7$ gal) of impounded tailings solution to the environment. As a result of this incident, the tailings impoundment was enlarged to its current capacity. The existing system, with a minimum of 1 m (3 ft) of freeboard, is estimated to provide 12.6 x $10^8$ liters (3.3 x $10^8$ gal) of emergency storage.

Reclamation of the site will begin after total evaporation of the ponds (estimated to be 6 to 8 years after cessation of operation). All contaminated areas will be buried under a layer of clay 0.3 m (1 ft) thick. Next, the area will be overlain with 1.2 m (4 ft) of subsoil material. An additional 0.15 m (0.5 ft) of plant-growth media or topsoil will then be spread over the surface. About 2 years would elapse before vegetation would be established. The estimated cost of this program is about $7,000,000 (1979 dollars) (NRC84).

### Shirley Basin

The Shirley Basin Uranium Mill owned by Pathfinder Mines Corporation is located in an area of plains and rolling hills about 72 km (45 mi.) south of Casper, Wyoming. The mill, which began operation in 1971, uses semi-autogenous grinding, leaching, and ion exchange. Current mill capacity is 1600 t of ore per day (NRC84). Current throughput is 900 t per day (SI85). Operations are projected to continue through 1994.

Tailings are contained in a single onsite tailings pile that is contained above-grade by a single-sided earthen retention dam 18 m (60 ft) high. The tailings cover about 260 acres, of which about 190 acres is tailings solution. The pond contains 5.8 x $10^6$ t of tailings (Si85). The tailings are reported to contain 540 pCi/g of radium-226 (EPA83b). A site map or diagram was not available.

A 1983 survey of the population in the vicinity of the Shirley Basin Mill indicated that no inhabitants lived within 5 km (3.1 mi.) of the tailings pile (EPA83).

## Highland Mill

Exxon's Highland Mill is located about 100 km (60 mi.) northeast of Casper, Wyoming, in a rolling hills area of the Powder River Basin. Milling operations at this site began in 1972, but it is currently being decommissioned.

Mill tailings are contained in a natural valley behind an earthen embankment. The pile covers 200 acres and contains about 7 x $10^6$ t of tailings. The tailings are reported to contain 450 pCi/g of radium-226 (EPA83b). A site map or diagram was not available.

A 1983 survey of the population in the area indicated that no inhabitants lived within 3 km (1.9 mi.) of the tailings pile. Only six inhabitants, who lived between 3 and 4 km (1.9 and 2.5 mi.) from the pile, resided within 5 km (3.1 mi.).

## Split Rock Mill

Western Nuclear's Split Rock Mill is located 3.2 km (2 miles) north of Jeffrey City, Wyoming. The mill, which began operation in 1957, has been on standby status since June 1981. When running at capacity, the mill produced 850 t of yellowcake per year (Bo85). Maximum throughput was about 1500 t of ore per day (NRC84). The ore grade has ranged from 0.15 to 0.30 percent $U_3O_8$ in the past and is expected to range from 0.05 to 0.15 percent in the future (NRC84). Milling operations involve semiautogenous grinding, an acid leach, and solvent extraction. The mill usually stockpiles 1800 to 4500 t of ore when it is operating. Two 8-m (25-ft) diameter bins are used to store fine ore.

The tailings generated by the Split Rock Mill are contained in a single tailings pile that is enclosed by an earthen dam. The tailings pile has a surface area of about 125 acres and a maximum depth of about 29 m (95 ft)(Bo85). About 80 acres of the pile is covered by tailings solution (Bo85). Tailings are discharged from the crest of the dam; the point of discharge is periodically moved along with the crest. Western Nuclear uses a sprinkler system to control dusting from the pond during non-freezing months. Wind fences, chemical sprays, and vegetation seeding are also used to control dusting. About 11 x $10^6$ t of commingled tailings are under plant management (NRC84).

The average radium-226 concentration of the tailings is approximately 100 pCi/g (99.5 ± 42 pCi/g) (Bo85). Radium-226 values in the sands and slimes were determined to be 63 pCi/g and 87 pCi/g, respectively (Bo85). Western Nuclear has used charcoal filters to measure radon-222 flux from the tailings. The flux measurements, made in 1977-1978, were 2 ± 1.1 $pCi/m^2$-s (Bo85). The earlier EPA report indicated that 430 pCi/g of radium-226 was present in the tailings (EPA83b).

Western Nuclear estimates that less than 700 people live in Jeffrey City, which is about 3.2 km (2 mi.) from the mill (Bo85). A 1983 population survey conducted by the EPA indicated that three people lived between 0.5 and 1.0 km (0.3 and 0.6 mi.) from the tailings pile. This survey also indicated 30 people residing between 2 and 3 km (1.25 and 1.9 mi.) away, 697 between 3 and 4 km (1.9 and 2.5 mi.), and 176 between 4 and 5 km (2.5 and 3.1 mi.) away from the tailings pile (EPA83b).

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# Chapter 4: RADON-222 EMISSIONS FROM LICENSED MILLS AND TAILINGS PILES

## 4.1 Description of Radon-222 Sources

Ore stockpiles, crushing and grinding operations, the extraction circuit, and tailings piles are the significant sources of radon-222 at operational uranium mills. Other sources, such as contaminated former ore storage areas and raffinate ponds, also may release radon-222. These sources, however, are considered to be comparatively small and of such uncertainty in size, source strength, and frequency of occurrence that they are omitted from the present analyses. As illustrated in Figure 4-1, radon-222 releases can be characterized as total-release events or continual, diffusion-limited releases.

Thick sources that remain undisturbed for extended periods of time release radon-222 by diffusive and advective mechanisms. Accordingly, the radon-222 emission is characterized by a normalized radon-222 flux expression. Ore storage pads and mill tailings piles are examples of this type of source. Conversely, sources that rapidly release radon-222 during a mechanical disturbance, such as the crushing and grinding operation, are best characterized by a radon-222 release per unit mass; e.g., pCi of radon-222 per pound of $U_3O_8$ produced by the mill. The radon-222 release rate of these sources is readily associated with the milling rate and ore grade.

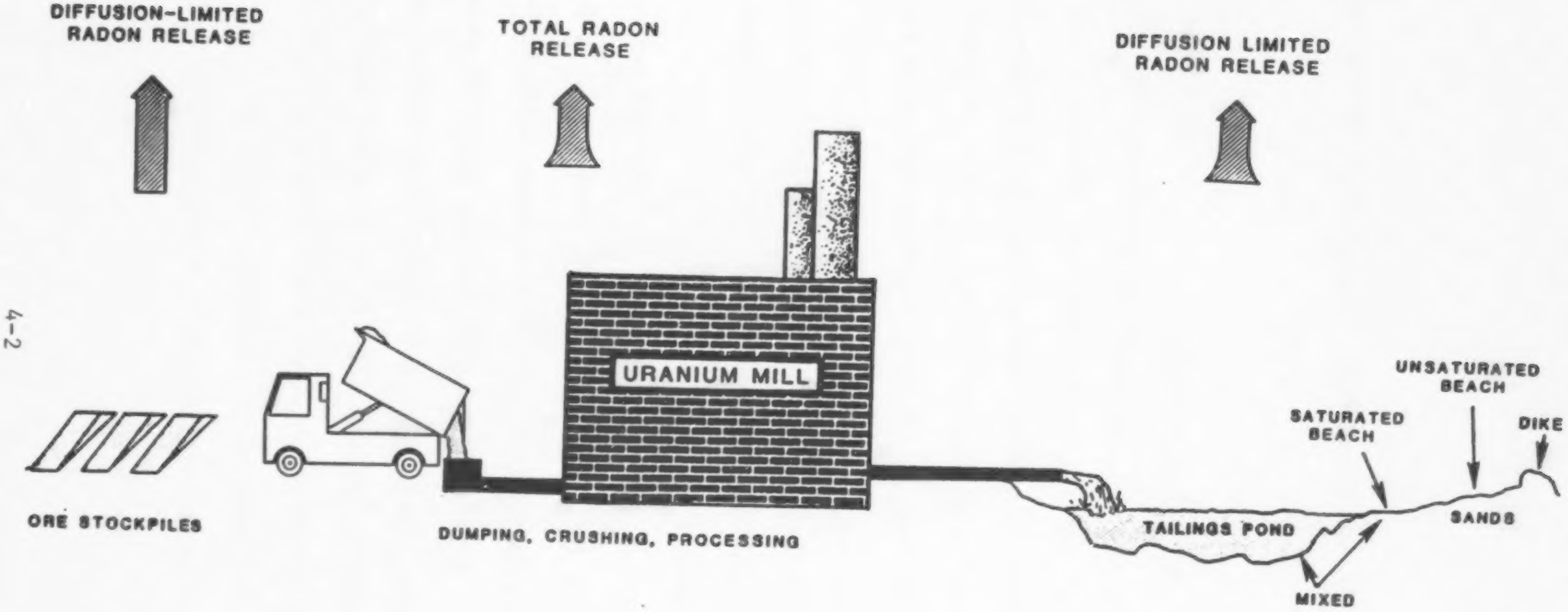
DIFFUSION-LIMITED RADON RELEASE
TOTAL RADON RELEASE
DIFFUSION LIMITED RADON RELEASE
URANIUM MILL
ORE STOCKPILES
DUMPING, CRUSHING, PROCESSING
UNSATURATED BEACH
SATURATED BEACH
DIKE
SANDS
TAILINGS POND
MIXED

Figure 4-1. Schematic illustration of the radon sources at a uranium mill.

The following descriptions characterize these releases. Finally, estimates are made of the quantity of radon-222 emitted from each licensed uranium mill.

Details of the estimating procedure are contained in Appendix B.

## Radon-222 Emissions from Ore Storage Piles

Ore stockpiles are maintained on site at operational mills to provide a reserve ore supply to enable the mill to operate efficiently despite possible irregularities in the ore production rate at the mine. The stockpiles also provide a source where the various grades of ore can be blended to match the optimum uranium concentrations for the mill's extraction process. The numbers and sizes of these ore stockpiles are not well known. A survey of eight mills in Wyoming showed a wide range in the number of ore stockpiles, their sizes, and the average residence time of the stockpiled ores (Ni79, Th82). The ore residence times varied from 4 to 180 days, with a mean and standard deviation of 87 ± 72 days (Th82). Although these findings are largely consistent with information on ore storage obtained during the current project, some exceptions were noted. For example, Dawn Mining reports that its ore stockpile at the Ford Mill is maintained at a level that would supply milling requirements for a full year. In addition, during the period when mills are on standby status, as most in the industry now are, no ore is stockpiled at the mill. During standby status therefore, no significant quantity of radon-222 is emitted from the mill because stockpiles are absent and the milling circuit empty.

Radon-222 emissions from the ore stockpiles may be modeled in terms of discrete piles of fixed sizes. The number of piles is determined by the product of the mill feed rate (tons/day) and the stockpile residence time (days) divided by the mass of a pile (tons). The shape of the piles varies among different mills, but it is frequently conical, oblong, or a wedge. A maximum height of 30 ft and 45-degree sloping sides are common. The volume and surface area of a typical pile is estimated to be 8000 $m^3$ and 2500 $m^2$, respectively (Th82). Stockpiles are considered to emit radon-222 from an infinitely thick source from all surfaces, even though some parts may be thin. This gives a conservatively high radon-222 estimate for some of the pile areas, but is justified by the variable sizes, shapes, and other characteristics of the ore stockpiles.

Stockpiles initially emit no radon-222 because all of the emanated radon-222 stored in the pores of the ore was released as the ore was removed from the mine and transported to the stockpiles. As new radon-222 is emanated into the pore space of the ore, the interstitial radon-222 levels and the escaping radon-222 flux increase with the 3.8-day halflife of radon-222. After several weeks, a nearly constant radon-222 flux is attained. The radium-226 content used in the calculations is estimated from ore grades, assuming secular equilibrium between the uranium-238 and the radium-226.

## Radon-222 Emissions from Milling Operations

The uranium mill uses physical and chemical processes to remove uranium from the ore. These processes can be categorized as crushing and grinding to reduce the ore to a small particle size, and leaching and extraction to dissolve and remove the uranium. Due to the finite size of most uranium mills and their relatively large throughput (thousands of tons per day), the residence time of ore in the mill is less than one day.

The total release of radon-222 from the dumping, crushing, and extraction processes occurs mostly during the process of transferring and dumping the ore into the mill feed area because the ore has typically been reduced to sizes of less than 40 cm, the relaxation diameter for ore pieces with diffusion coefficients of $10^{-3}$ $cm^2/s$. Radon-222 therefore escapes readily from the pores of the ore when it is handled, causing the total release of accumulated radon-222. During the remainder of the short milling process, the ore produces little additional radon-222 for release.

An exception to this description is hard-rock uranium ores that have very low diffusion coefficients for radon-222 ($10^{-4}$ to $10^{-5}$ $cm^2/s$). For these ores, 4- to 14-cm particles can significantly reduce radon-222 releases, and hence the sharp one-time release shown in Figure 4-2 is reduced and delayed somewhat until the ore is ground to smaller particle sizes during milling.

## Radon-222 Emissions from Tailings Piles

With the exception of the uranium product, the tailings coming from the mill contain virtually all of the radium-226 and other radionuclides present in the ore. These tailings are then discharged as a slurry to tailings piles. The tailings discharge point is typically moved to different positions around the edge of the tailings pond so that the sands, which settle most readily, deposit at the outer edges of the pond while the slimes concentrate closer to the center.

Tailings initially entering the pile are depleted in free, gaseous radon-222, and require several days to contribute to the total radon-222

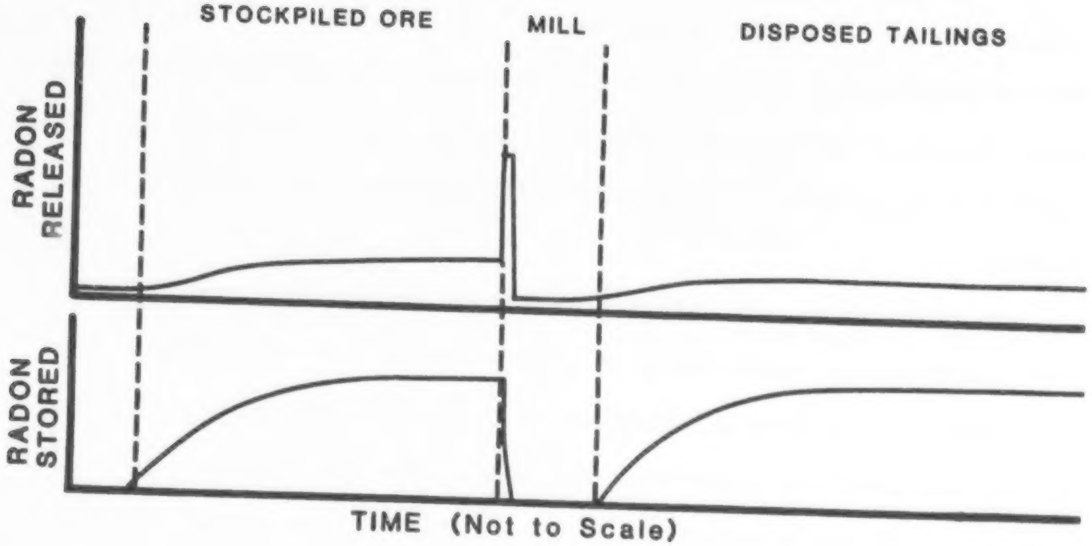

Figure 4-2. Time sequence of gaseous storage and release from the active uranium mill.

flux (Figure 4-2). Since the daily input of new tailings is small compared with the total mass of existing tailings, however, the new additions have no significant impact in lowering the rate of radon-222 emission.

The surface area of a tailings pile is a controlling factor in determining the quantity of radon-222 released. Accurate measurements of surface areas of tailings piles at licensed mills are not available. Typically, the only reasonably accurate measurement available is the area covered by the base of the pile. The area covered by tailings solution is most often approximated based on visual observation by the operator. The surface area of this water-covered area changes with time and operational conditions. The accuracy of the estimates of radon-222 emissions from tailings piles is limited by the accuracy of the reported dimensions of these piles.

Additionally, actual measurements have not been compiled of other variables important in estimating radon-222 source terms. Particle size, moisture content, radon-222 emanation coefficients and radium-226 content have not been widely characterized. For example, previous estimates have used average radium-226 contents and have assumed homogeneity of the pile. But radium-226 content of tailings varies from site to site due to differences in ore and varies with time at a given site due to variations in the ore grade. In addition, the piles are not homogeneous with regard to radium-226. The slime fraction contains significantly more radium-226 than the sand fraction. Measurements or estimates of average radium-226 contents of tailings at specific mills are contained in past documents (EPA83, NRC84). Many operators contacted during this study could not characterize the radium-226 content of sands and slime tailings at their mills. This lack of an accurate and reliable data base on radium-226 content of tailings limits the accuracy of any estimates of radon-222 released.

## 4.2 Estimation of Radon-222 Emissions

Several reports present estimates of radon-222 emissions from licensed mills. These include NRC's FGEIS (NRC80), EPA's EIS for uranium ore processing (EPA83), and EIS documents prepared for specific mills. A summary of the estimates presented in the EPA report is shown in Table 4-1. The estimates in each report are based on the same set of assumptions. Radon-222 emissions from tailings are assumed to be 1 pCi/m$^2$-s per pCi radium-226 present in 1 gram of tailings (NRC80) for piles that are dry, homogeneous, uncovered, and at least 3 meters deep. This assumption doesn't account for the limiting effects of moisture and water cover present during the operational phase (EPA83). In comparison, Haywood calculated values of 0.35, 0.65, and 1.2 pCi/m$^2$-s per pCi/g radium-226 for wet, moist, and dry tailings, respectively (Ha77, EPA83). In addition, the accuracy of the estimate for a specific site is limited because of the lack of accurate data on surface areas of piles, radium-226 content of tailings, and radon-222 emanation coefficients, particle size, moisture content, and other variables.

An effort was made to refine the estimate of radon-222 emissions from tailings piles at licensed mills by applying the standard radon-222 flux of 1 pCi/m$^2$-sec per pci radium-226/g to the current information (surface area and radium-226 content) on these piles presented in Chapter 3. Additionally, a new set of radon-222 fluxes for dry, wet, and water

Table 4-1. Estimates of radon-222 releases from tailings piles at licensed uranium mills[a]

| Location/Company | Tailings pile area (acres) | Radium-226 content (pCi/g) | Estimated radon-222 release[b] (kCi/y) |
|---|---|---|---|
| Colorado | | | |
| Canon City/Cotter | 165 | 780 | 20 |
| Uravan/Union Carbide | 85 | 480 | 4.8 |
| New Mexico | | | |
| L-Bar/Sohio | 140 | 500 | 11 |
| Churchrock/UNC | 200 | 290 | 7.4 |
| Bluewater/Anaconda | 300 | 620 | 21 |
| Ambrosia Lake/Kerr-McGee | 328 | 620 | 20 |
| Grants/Homestake | 210 | 385 | 9.7 |
| South Dakota | | | |
| Edgemont/TVA | 123 | 560 | 8.9 |
| Texas | | | |
| Falls City/Conoco | 240 | - | - |
| Pana Maria/Chevron | 160 | - | - |
| Ray Point/Exxon | 47 | 520 | 3.1 |
| Utah | | | |
| Blanding/Energy Fuels | 116 | 350 | 5.2 |
| LaSal/Rio ALgom | 100 | 560 | 3.2 |
| Moab/Atlas | 128 | 540 | 7.8 |
| Washington | | | |
| Ford/Dawn | 133 | 850 | 11 |
| Wellpinit/Western Nuclear | 89 | 200 | 1.1 |
| Wyoming | | | |
| Gas Hills/FAP | 117 | 420 | 5.6 |
| Gas Hills/Pathfinder | 248 | 420 | 4.0 |
| Jeffrey City/Western Nuclear | 167 | 430 | 4.8 |
| Gas Hills/Union Carbide | 146 | 310 | 5.9 |
| Powder River/Exxon | 200 | 450 | 12 |
| Powder River/Rocky Mountain | 120 | 420 | 8 |
| Shirley Basin/Pathfinder | 400 | 540 | 10 |
| Shirley Basin/Petrotomics | 140 | 570 | 12 |
| Red Desert/Minerals Exp. | 174 | 280 | 6.2 |
| Total | 4,276 | - | 203[c] |

[a] EPA83.

[b] Assumes radon-222 emission rate of 1 pCi/m$^2$-s per pCi/g of radium-226. Does not account for effect of moisture content or water cover.

[c] Does not include releases from piles where estimate was not obtained.

covered tailings was developed for tailings piles and other radon-222 emissions points at licensed mills. These new estimates of radon-222 released from tailings are based on standard radon-222 diffusion and transport equations (Ro84, NRC80) along with newly measured data on radon-222 transport rates through water. Details of the calculations are included in Appendix B.

Radon-222 emission-rate expressions for each source were normalized to the radium-226 or equivalent uranium in the ore materials or tailings. Releases from milling were normalized to the milling or production rate. These estimates also take into account the variability of radon-222 emissions by geographical region. This variability is denoted by average characteristics, based on site specific information, for each uranium milling state. Parameters causing variation include radon-222 emanation coefficient and meteorological conditions such as precipitation, ambient temperature, and evaporation.

In order to estimate the release of radon-222 from operational uranium mills, a variety of site-specific parameters are defined. Although some of these parameters such as ore grades and surface areas of the tailings piles are readily known or measurable, others such as radon-222 diffusion coefficients and radon-222 emanation coefficients are usually unknown and must be estimated without direct site-specific measurements. Available site-specific information was used for these estimates. When the required data were not available, assumptions were used as the basis for estimating the parameters of concern. The parameters that must be defined, the basis of the assumptions, and the calculations are contained in Appendix B. The radon-222 emission rates that resulted from these calculations are presented in Table 4-2.

Table 4-2. Estimated radon-222 emission rates for major radon-222 sources at licensed mills in each uranium milling state

| Radon-222 source | Units | Radon-222 emission rate | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | CO | NM | TX | UT | WA | WY | Mean |
| Ore stockpiles | pCi $m^{-2}s^{-1}$/pCi $g^{-1}$ | 0.58 | 0.98 | 0.18 | 0.41 | 0.32 | 0.56 | 0.51 |
| Ore handling | pCi/lb $U_3O_8$ | 3.2E7 | 6.2E7 | 3.4E7 | 2.6E7 | 3.2E7 | 3.4E7 | 0.7E7 |
| Ore milling | pCi/lb $U_3O_8$ | 5.1E6 | 9.3E6 | 4.6E6 | 4.0E6 | 4.6E6 | 5.3E6 | 0.5E6 |
| Unsaturated tailings | pCi $m^{-2}s^{-1}$/pCi $g^{-1}$ | 0.42 | 0.76 | 0.23 | 0.29 | 0.29 | 0.43 | 0.40 |
| Saturated tailings | pCi $m^{-2}s^{-1}$/pCi $g^{-1}$ | 0.036 | 0.062 | 0.031 | 0.027 | 0.031 | 0.035 | 0.037 |
| Tailings pond | pCi $m^{-2}s^{-1}$/pCi $g^{-1}$ | 0.020 | 0.033 | 0.019 | 0.017 | 0.019 | 0.021 | 0.022 |

Mean emission rates for unsaturated tailings, saturated tailings, and water-covered tailings are 0.40, 0.04, and 0.02 pCi/m$^2$-s per pCi radium-226/g tailings. These estimates are lower than those by Haywood who estimated rates of 1.2, 0.65, and 0.35 pCi/m$^2$-s per pCi radium-226/g tailings for dry, moist, and wet tailings (Ha77). They are also lower than the emission rate assumed for dry tailings in NRC's FGEIS (1 pCi/m$^2$-s per pCi radium-226/g) (NRC80). Previous estimates used a value of 0.2 for the radon-222 emanation coefficient, while the current estimate used values ranging from 0.18 for sites in Utah to 0.41 for sites in New Mexico.

A summary of the results of the calculations to estimate current radon-222 emissions from tailings piles at licensed uranium mills is presented in Table 4-3. Two sets of estimates are made. The standard radon-222 flux of 1 pCi/m$^2$-s per pCi radium-226/g tailings is applied to available site-specific information to estimate annual radon-222 releases. For these calculations it is assumed that radon-222 does not emanate from water-covered portions of the piles. Additionally, a second set of estimates are made based on the radon-222 emission rates developed in Appendix B. This second set of estimates was made in an effort to corroborate the standard set of assumptions that are used in estimating radon-222 emissions.

In order to assess the relative importance of the six radon-222 source components listed, an example calculation of total radon-222 emissions was made. In the following example, a uranium mill in Wyoming is defined to have a production rate of 1500 tons/day, with an average ore grade of 0.1 percent $U_3O_8$. It is also defined to have an average ore stockpile residence time of 87 days, and to have nominal densities and

Table 4-3. Estimates of radon-222 currently released from tailings piles at licensed uranium mills

| Location/company | Area of exposed tailings (acres) | Water-covered area (acres) | Radium-226 content (pCi/g) | Estimated radon-222 release (kCi/y) Standard method(a) | New method(b) |
|---|---|---|---|---|---|
| **Colorado** | | | | | |
| Canon City/Cotter | 100 | 100 | 780 | 0 | 0.2 |
| Uravan/Union Carbide | 80 | 0(c) | 480 | 4.9 | 2.1 |
| **New Mexico** | | | | | |
| L-Bar/Sohio | 125 | 60 | 500 | 4.1 | 1.8 |
| Churchrock/UNC | 50 | 0(c) | 290 | 1.8 | 1.6 |
| Bluewater/Anaconda | 137 | 22 | 520 | 7.7 | 4.8 |
| Quivira/Kerr-McGee | 315 | 40 | 620 | 22. | 12. |
| Grants/Homestake | 170 | 100 | 385 | 3.4 | 2.0 |
| **South Dakota** | | | | | |
| Edgemont/TVA | 123 | 0 | 560 | 8.8 | 3.5 |
| **Texas** | | | | | |
| Panna Maria/ Chevron | 140 | 110 | NA(d) | - | - |
| Conquista/ Continental | 250 | 50 | NA(d) | - | - |
| **Utah** | | | | | |
| Moab/Atlas | 125 | 0(c) | 540 | 8.6 | 2.5 |
| Shootaring/Plateau Resources | 10 | 3 | NA(d) | - | - |
| White Mesa/Energy Fuels | 80 | 0 | 350 | 3.6 | 1.0 |
| Libson/Rio Algom | 35 | 17 | 560 | 1.2 | 0.4 |
| **Washington** | | | | | |
| Ford/Dawn | 139 | 28 | 850 | 12. | 3.6 |
| Sherwood/Western | 135 | 60 | 200 | 1.9 | 0.6 |

Table 4-3 (Continued)

| Location/company | Area of exposed tailings (acres) | Water-covered area (acres) | Radium-226 content (pCi/g) | Estimated radon-222 release (kCi/y) | |
|---|---|---|---|---|---|
| | | | | Standard method(a) | New method(b) |
| **Wyoming** | | | | | |
| Shirley Basin/ Petrotomics | 140 | 63 | 558 | 5.5 | 2.4 |
| Sweetwater/Minerals Exploration | 42 | 40 | 280 | 0.1 | 0.03 |
| Bear Creek/Rocky Mt. Energy | 120 | 25 | 420 | 5.1 | 1.8 |
| Gas Hills/ANC | 116 | 0 | 420 | 6.2 | 2.7 |
| E. Gas Hills/ Union Carbide | 186 | 14 | 310 | 6.8 | 2.9 |
| Gas Hills/ Pathfinder | 160 | 140 | 160 | 0.4 | 0.2 |
| Shirley Basin/ Pathfinder | 260 | 190 | 540 | 4.8 | 2.4 |
| Highland/Exxon | 200 | 0 | 450 | 11.5 | 4.9 |
| Split Rock/ Western Nuclear | 125 | 80 | 100 | 0.6 | 0.3 |
| Total | 3360 | 1140 | | 120(e) | 54(e) |

(a) Standard method of estimation uses radon-222 flux of 1 $pCi/m^2$-s per pCi radium-226/g tailings. Water-covered areas of tailings piles were assumed to not emit radon-222.

(b) New method of estimation uses radon-222 flux values given in Table 4-2.

(c) Assumed value.

(d) Not available.

(e) Does not include releases from piles where estimate was not obtained.

other parameters as defined for Wyoming operations (Appendix B). The total area of the ore stockpiles was estimated to be 21,000 $m^2$. The tailings area covered 170 acres, of which 22 acres were dry sands, 50 acres were saturated beaches, and 100 acres were covered with tailings solution. Radon-222 release rates for each source were computed to be:

| Radon-222 source | Ci/day | Percent of total |
|---|---|---|
| Ore stockpiles | 0.3 | 17 |
| Ore handling | 0.1 | 6 |
| Ore milling | 0.2 | 1 |
| Unsaturated tailings | 0.9 | 52 |
| Saturated tailings | 0.2 | 12 |
| Pond area | 0.2 | 12 |
| Total | 1.7 | 100% |

At this example site, the tailings contribute 76 percent of the total radon-222 emitted and the ore handling and stockpiles contribute 23 percent. The milling operation contributes the small remainder.

## 4.3 Application to Specific Facilities

The estimated emission rates of Table 4-2 were applied to the Homestake mill near Grants, New Mexico, and the Petrotomics mill in Shirley Basin, Wyoming, to estimate the total amount of radon-222 emitted from each of these two sites. In one case, site-specific information was obtained from a brief site visit and in the other case from telephone conversations with the operator. The appropriate surface areas are multiplied by the emission rate factors in Table 4-2 and radium-226 content to obtain total emissions per second. This rate is then converted to emissions per year. Emissions from ore handling and leaching are based on annual production rates of $U_3O_8$.

**Homestake Mill**

1. Ore Stockpile

   2460 $m^2$ x 0.98 $pCi/m^2$-s per pCi Ra-226/g x 396 pCi Ra-226/g x (3.15 x $10^7$ s/y) x ($10^{-12}$ pCi/Ci) = 30 Ci/y

2. Ore Handling

   (4.4 x $10^5$ lb $U_3O_8$/yr) x (6.2 x $10^7$ pCi/lb) x $10^{-12}$ pCi/Ci = 30 Ci/y

3. Ore Leaching

   (4.4 x $10^5$ lb $U_3O_8$/yr) x (9.3 x $10^6$ pCi/lb) x $10^{-12}$ pCi/Ci = 4 Ci/y

4. Unsaturated tailings

   194,000 $m^2$ x 0.71 $pCi/m^2$-s per pCi/g x 396 pCi/g x (3.15 x $10^7$ s/y) x $10^{-12}$ pCi/Ci = 1700 Ci/y

5. Wet Beach

   52,940 $m^2$ x 0.058 $pCi/m^2$-s per pCi Ra-226/g x 396 pCi/g x (3.15 x $10^7$ s/y) x $10^{-12}$ pCi/Ci = 40 Ci/y

6. Pond Area

   384,000 $m^2$ x 0.032 $pCi/m^2$-s per pCi Ra-226/g x 396 pCi/g x (315 x $10^7$ s/y) x $10^{-12}$ pCi/Ci = 150 Ci/y

   Total radon-222 emission = 2000 Ci/y

**Petrotomics Mill**

The Petrotomics mill is on standby status; therefore, no radon-222 is emitted from ore storage, handling, or extraction. The tailings dam is earthen, and no dry tailings sands are exposed. Wet beach area covers about 77 acres, and the pond covers approximately 63 acres.

Wet Beach

$311{,}542\ m^2 \times 0.43\ pCi/m^2\text{-}s$ per pCi Ra-226/g $\times 558\ pCi/g \times$
$(3.15 \times 10^7\ s/y) \times (10^{-12}\ pCi/Ci) = 2400\ Ci/y$

Pond Area

$254{,}900\ m^2 \times 0.021\ pCi/m^2\text{-}s$ per pCi Ra-226/g $\times 558\ pCi/g \times$
$(3.15 \times 10^7\ s/y) \times (10^{-12}\ pCi/Ci) = 100\ Ci/y$

Total radon-222 emission = 300 Ci/y

In comparison with our estimate of 2000 Ci/y for the Homestake mill and tailings pile, the radon-222 emission rate has been previously estimated to be about 5700 Ci/y (Mi85). The difference is due mainly to the fact that the 5700 Ci/y is based on the assumptions that the radon-222 flux from tailings is 1 $pCi/m^2$-s per pCi of radium-226/g, and a radon-222 emanation coefficient of 0.2. The new estimate uses emission rates of 0.7, 0.06, and 0.03 $pCi/m^2$-s per pCi of radium-226/g in the dry, saturated, and water-covered tailings and uses an emanation coefficient of 0.39, which is believed to be more accurate for this site. A previous EPA estimate (EPA83) concluded that about 9700 Ci/yr are released from the Homestake tailings pile alone. This estimate assumed an emission rate of 1 $pCi/m^2$-s per pCi of radium-226/g of tailings and assumed the pile was dry. No comparison can be made for the Petrotomics mill and tailings pile because it is relatively new and was not included in the previous EPA estimate.

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# Chapter 5: CONTROL PRACTICES AND COST

## 5.1 Introduction

Currently, no radon-222 controls are used at licensed mills or their active tailings disposal areas. Dust emission control is practiced to minimize airborne particulate, but no controls are used specifically for radon-222.

Reducing radon-222 emissions to air from active tailings piles is not easily accomplished since tailings are continuously added to the pile. With inactive piles, earth cover material may be applied and radon-222 emissions reduced. With active piles, however, tailings are continually dumped and the solids allowed to settle out. In addition, the shape and stability of a pile or dam limits the amount of water or earth cover that can be safely applied.

Radon-222 controls for other parts of the mill circuit or at the ore storage area at existing mills are not used at operating uranium mills. Potential controls for these sources are not discussed further in this report since they represent a small portion of the total radon-222 emissions.

This section describes the control practices that can be applied to active tailings areas, their approximate cost, and their effectiveness. Most of the information was obtained from previous NRC studies.

### 5.2 Control Practices for Active Tailings Areas

The most feasible method for reducing radon-222 emissions from active tailings areas depends on the specific characteristics of the milling process and the pile. These characteristics include: layout and dike construction, dike height, stability, phreatic level and permeability, type of milling process (acidic or alkali), plant water balance, pond evaporation rates, and availability of suitable earth cover material. The following sections describe practices that could be adopted at existing tailings storage areas. These practices could be more easily adapted to new tailings disposal areas because they could be incorporated into their initial design.

#### 5.2.1 Earth Covers

Covering the dried beach area with soil could be an effective method for reducing radon-222 emissions. This method has been widely used at inactive tailings piles. The depth of soil required for a given amount of control varies with the type of soil.

Soil cover is useful in decreasing radon-222 emissions because of their ability to restrict the diffusion of radon-222 long enough so that it will decay into a solid product and remain trapped in the cover material. Radon-222 diffusion through soil is a complex phenomena affected by macroscopic processes such as groundwater flow and complex microscopic processes such as molecular diffusion described mathematically by Fick's law. These complex diffusion parameters have been evaluated by Rogers and Nielson (Ro81).

They determined that the diffusion coefficient is strongly dependent on the porosity and moisture content of the medium through which diffusion occurs. Ideally, the diffusion coefficient should be measured experimentally for a given soil cover at its ambient moisture content and expected compaction level. This coefficient can, however, be estimated based on moisture content and porsity of the material. Clay soils have superior moisture retention (9 to 12 percent moisture) and are best for covering tailings; clay soils are found in the uranium milling regions of Colorado, New Mexico, Utah, and Wyoming (Ro81).

At active piles, only those portions that are not to be used further could be covered. Which portion and how much of the tailings area to cover is a function of anticipated mill life and quantity of tailings, size of tailings pile, and level of tailings. In addition, a source of cover material must be obtained and a technique must be developed for hauling, dumping, spreading and compacting the soil onto the beach area. The limited access of the tailings area and the stability of the dike may affect the size of the equipment that can be used to transport and spread the cover material. Additional soil may have to be added to the dike sides to decrease their slope and increase stability. Metal gratings or timbers may be required to distribute vehicle wheel loads on the dike or dried beach area.

When a new tailings pile is planned and laid out, a network of earth partitions can be constructed to create cells or segments. Partitioning allows sections of the pile to be used independently of other sections. After a section has been used for a year or two, it can be covered and another section used. In practice, two below-grade lined pits would be constructed. Tailings are pumped to one pit until it is full. This pit is then left to dry and tailings are pumped to the second pit. After the first pit drys, it is covered with earth obtained from the construction of a third pit. This process is continued sequentially. This system reduces total emissions since a section can be covered after use without interfering with disposal operations. Less total surface area is thus exposed at any time.

## Cost and Effectiveness

The effectiveness of various types of soil cover in reducing radon-222 emissions is shown in Figure 5-1. This chart is based on an emission rate of 280 pCi/m$^2$-s for uncovered tailings and shows the emission rate after various depths of soil are applied. The diffusion coefficients for different types of soils and their moisture content are shown. The high- moisture content soils provide great radon-222 emission reduction because of their smaller diffusion coefficient. With even the "best" soil cover, a thickness of 1 to 2 meters is required to effect a significant reduction in emissions to the air. Table 5-1 presents estimated earth cover thicknesses to reduce emissions to 20 pCi/m$^2$-s.

Table 5-1. Estimated earthen cover thickness (in meters) needed to reduce radon-222 emissions to 20 pCi/m$^2$-s (EPA 83)

| Radon-222 emission from tailings (pCi/m$^2$-s) | Percent moisture in earth cover | | | |
|---|---|---|---|---|
| | 6 | 8 | 10 | 12 |
| 100 | 1.7 | 1.3 | 1.0 | 0.7 |
| 300 | 2.8 | 2.1 | 1.5 | 1.1 |
| 500 | 3.4 | 2.6 | 2.0 | 1.5 |
| 1000 | 4.1 | 3.2 | 2.4 | 1.8 |

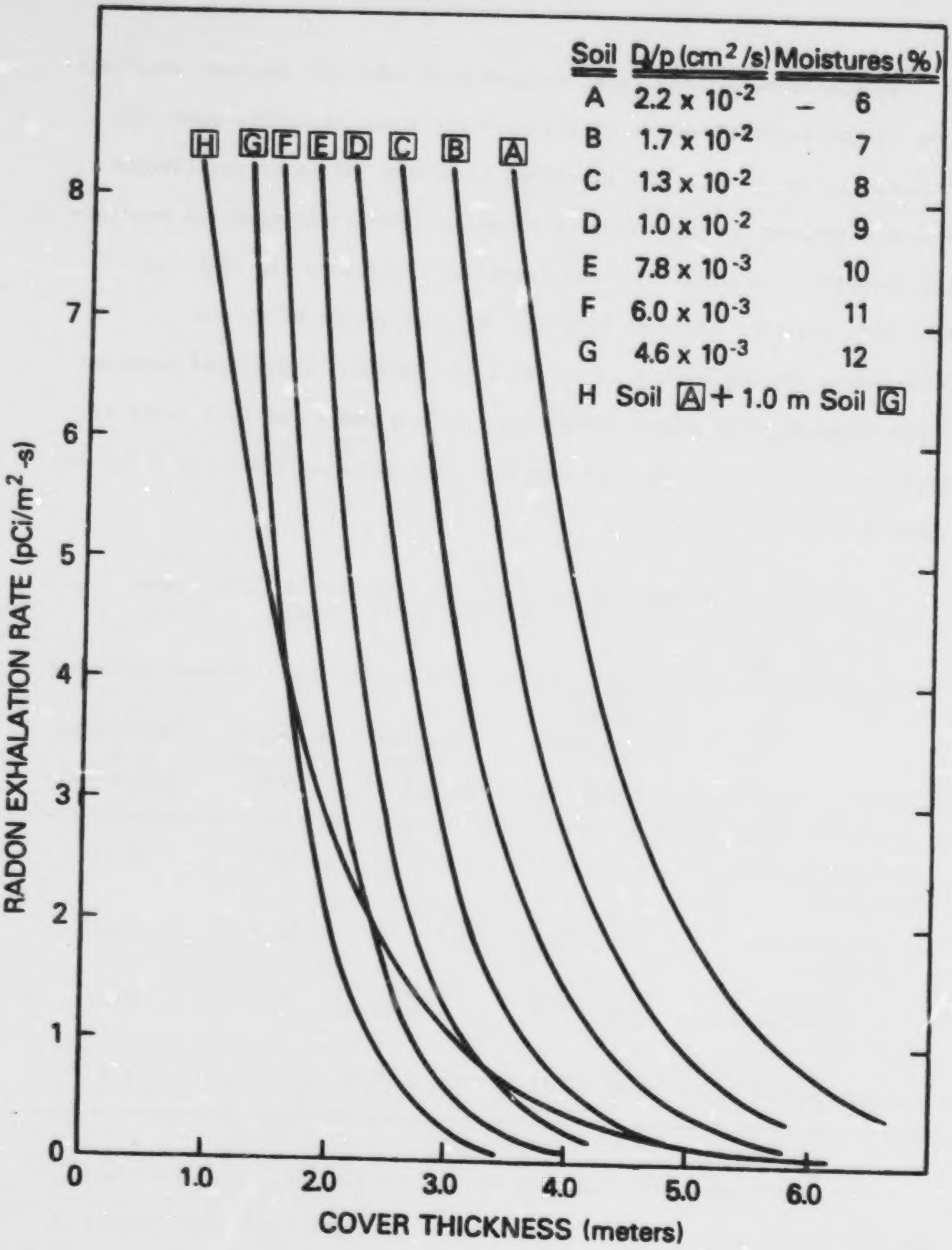

Figure 5-1. Effect of soil thickness on radon-222 exhalation rate (Ro81).

In practice, earthen cover designs must take into account uncertainties in the measured values of the specific cover materials used, the tailings to be covered, and predicted long-term values of equilibrium moisture content for the specific location. The uncertainty in predicting reductions in radon-222 flux increases rapidly as the required radon-222 emission limit is reduced. Even at 20 pCi/m²-s, the uncertainty may approach a factor of three (Ro83). Calculated emission rates using Roger's method (Ro81) for four earthen cover test plots at Grand Junction, Colorado, were compared with measured values as shown in Table 5-2 (Ba82, Ha83).

Table 5-2. Summary of radon-222 flux measurements at Grand Junction over a two-year period (Ba82)

| Radon-222 barrier | Average tailings source flux (pCi/m²-s) | Average flux (pCi/m²-s) | Moisture content (%) | Calculated flux (pCi/m²-s) |
|---|---|---|---|---|
| 1.2 m mancos shale/ 1.8 m adobe | 619 ± 221 | 1.0 ± 1.1 | 15.8 | 2.32 |
| 1.2 bentonite/ 1.8 m adobe | 589 ± 285 | 8.8 ± 8.5 | 20.2 | 0.07 |
| 1.2 m compacted adobe/ 1.8 m adobe | 316 ± 1 | 6.6 ± 10.2 | 11.9 | 6.92 |
| 3 m uncompacted adobe | 195 ± 132 | 18.3 ± 25.2 | 6.5 | 14.9 |

The third and fourth examples yielded fairly close results. Case one was off by a factor of 2 and case two was off by a factor of over 100.

The cost of adding soil covers varies widely with location of the tailings pile, its layout, and availability of soil. Costs depend upon the topography of the disposal site, its surroundings, and hauling distance. Another factor affecting costs of cover material is ease of excavation and the type of excavating equipment used. In general, the more difficult the excavation, the more elaborate and expensive the equipment and the higher the cost. The availability of such materials as clay or sand will affect costs. Large deposits of bentonite and similar clays are found in Wyoming and Utah and smaller deposits are found in all Western States. If the necessary materials are readily available locally, no incremental costs would be incurred; if they must be purchased and/or hauled, costs could increase significantly. A range of costs for soil cover is given in Table 5-3.

Table 5-3. Unit costs for estimating soil cover costs[a]

| Factor | Range of costs |
|---|---|
| Excavate, load, haul ($\leq$ 1 km), deposit | \$1.3 - \$1.7/m$^3$ |
| Truck transport ($\geq$ 1 km) | \$0.3 - \$0.4/m$^3$ |
| Spreading and compacting (cover and fill) | \$0.4 - \$0.7/m$^3$ |
| Compacting soil already in place | \$2700 - \$8300/ha |

[a] Based on NRC 80 information and updated to 1985.

Based on the cost factors and the required soil thickness shown in Figure 5-1, the resulting total costs per hectare for soil cover can be approximately estimated as shown in Table 5-4 for selected emission or flux levels. For example, to achieve an emission rate of 10 pCi/m$^2$-s with soil A would cost approximately \$74,000/hectare and require 3.3

Table 5-4. Cost (thousands of dollars per hectare)[a] of attenuating radon-222 flux as a function of thickness (meters of different soils) and type of soil coverings (NRC80)

| Flux ($pCi/m^2$-s) | Soil A | | Soil C | | Soil D | | Soil E | | Soil F | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cost | Thickness | Cost | Thickness | Cost | Thickness | Cost | Thickness | Cost | Thickness |
| 100 | 20 | 0.9 | 13 | 0.6 | 11 | 0.5 | 9 | 0.4 | 4.5 | 0.2 |
| 10 | 74 | 3.3 | 56 | 3.5 | 49 | 2.2 | 43 | 1.9 | 31 | 1.4 |
| 5 | 90 | 4.0 | 67 | 3.0 | 58 | 2.6 | 52 | 2.3 | 38 | 1.7 |
| 3 | 103 | 4.6 | 76 | 3.4 | 67 | 3.0 | 58 | 2.6 | 45 | 2.0 |
| 2 | 112 | 5.0 | 85 | 3.8 | 72 | 3.2 | 63 | 2.8 | 49 | 2.2 |
| 1 | 128 | 5.7 | 96 | 4.3 | 83 | 3.7 | 74 | 3.3 | 56 | 2.5 |

[a] Cost basis: $2.25/m$^3$ of cover material.

meters (10.8 feet) of cover. If half of an 80-hectare (200 acre) pond were to be covered, the cost would be about $15,700,000 and emissions would be reduced by almost 9.3 Ci/day.*

### 5.2.2 Water Cover

Maintaining a water cover over the tailings is expected to reduce radon-222 emissions. The degree of radon-222 control increases with the depth of the water and decreases with its radium-226 content. Factors affecting this practice include the mill water recirculation rate (if any), evaporation and precipitation rates, pile construction and slope, phreatic levels, groundwater contamination, and dike or dam stability. Some above-ground tailings piles minimize the depth of water in the pond to reduce seepage and possible groundwater contamination by draining the water through an overflow pipe to a separate lined evaporation pond.

For an existing above-ground tailings pile, many of these factors cannot be readily changed and the feasibility of water cover is limited mainly because of dike stability. Ideally, the pile would be constructed to allow approximately a 1-meter depth water cover with an overflow pipe leading to an adjacent evaporation pond and/or recycling to the plant. Only mills utilizing the alkali process can recycle water since acid mill tailings water contains too many impurities. To facilitate water cover, sufficient freeboard must be maintained to prevent overflow. For below-ground sites, this is not a problem. For above-ground piles, the pile sides would be raised as the pond fills with tailings by using the coarse fraction of the tailings or by using available earth material. When coarse tailings are used for the pond sides, a slurry cyclone can separate the coarse and fine fractions.

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*$(280-10) \times 10^{-12}$ Ci/m$^2$-s $\times$ 40 ha $\times$ $10^4$ m$^2$/ha $\times$ 86,400 s/day.

### Cost and Effectiveness

The diffusion coefficient of water is very low ($1.1 \times 10^{-5}$ cm$^2$/s) about one thousandth of a 9 percent moisture soil, and it is thus an effective barrier for radon-222. In shallow areas, radon-222 release is increased by thermal gradients and wave motion and emissions approach those of saturated tailings (Appendix B). Increased radium-226 content in the water reduces its effectiveness in controlling radium-226 since it releases radon-222.

If a pond is designed and built to maintain a water cover, there is no added cost for this form of radon-222 control. Continued monitoring is required to determine if there is any seepage through the dam or sides, and groundwater samples may be required periodically as a check for contamination.

### 5.2.3 Other Control Techniques

Water (or tailings liquid) sprays can be used to maintain a higher level of moisture in the tailings beach areas. This minimizes fugitive dust emissions and reduces the diffusion of radon-222 through the tailings. The effectiveness of this method varies with the moisture content of the tailings, and an approximately 10-fold decrease in the diffusion coefficient can be achieved for a 10 percent increase in moisture content (Ro81). Over longer periods of time, an overall radon-222 reduction of 20 percent has been estimated (NRC80). The annualized cost of such a system is approximately \$3400/ha* if operated 8 hours per day for 8 months per year.

Synthetic material such as polyethylene sheet can also reduce radon-222 emissions if carefully placed and sealed on dry beach areas. Diffusion coefficients of less than $10^{-6}$ $cm^2/s$ have been measured for synthetic materials (Ro81). Such covering could be used on a portion of the tailings area on a temporary basis and then removed or covered with fresh tailings. Such a barrier would also at least temporarily aid in the control of radon-222 if a soil cover material is applied.

The cost of installing polyethylene material is about \$0.01/$ft^2$ per mil of thickness or \$1.00/$ft^2$ for 100 mil material, which is equivalent to about \$107,600/ha (\$43,500/ac).

Chemical stabilization sprays that form coatings on the dry tailings are effective for controlling dust, but are not too useful for suppressing radon-222 since an impermeable cover is not obtained.

After dewatered tailings (25 - 30% moisture by weight) are dumped and spread over an impoundment area, they should be covered radidly. In one planned installation, tailings were dewatered by a belt filter system and trucked to a tailings disposal area where a 1-ft clay cap was then applied (Ma83). An active working edge of 300 ft was allowed for spreading, but no more than 10 acres of tailings was to be exposed at any one time. The clay cap was to be covered with 8 in. of gravel and about 8 ft of random fill. Additional random fill and overburden (up to 40 ft) from a surface mining operation were to complete the tailings cover.

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[*] Based on updated cost information in Reference EPA 83.

The ability of an existing plant to dewater tailings is very limited and would require major planning, design, and construction. Acid-based leaching processes do not generally recycle water, and additional holding ponds with ancillary piping and pumping systems would be required to handle the liquid removed from the tailings. Using trucks or conveyor systems to transport the tailings to disposal areas would also be more costly than using slurry pumping. Thus, although tailings are more easily managed by dewatering, this practice would have to be carefully considered on a site-specific basis.

# REFERENCES

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EPA83 Environmental Protection Agency, Final Environmental Impact Statement for Standards for the Control of Byproduct Material from Uranium Ore Processing, EPA 520/1-83-008-1, Office of Radiation Programs, Washington, D.C., September 1983.

Ha83 Hartley, J. N., Gee G. W., Baker E. G., and Freeman H. D., 1981 Radon-222 Barrier Field Test at Grand Junction Uranium Mill Tailings Pile DOE/UMT-0213, PNL-4539, April 1983.

Ma83 Marline Uranium Corp. and Union Carbide Corp. An Evaluation of Uranium Development in Pittsylvania County, Virginia. October 15, 1983. Section E.3.

NRC80 Nuclear Regulatory Commission, Final Generic Environmental Impact Statement on Uranium Milling, NUREG-0706, September 1980.

Ro81 Rogers V. C., and Nielson, K. K., A Handbook for the Determination of Radon-222 Attenuation Through Cover Materials, NUREG/CR-2340, Nuclear Regulatory Commission, Washington, D.C., December 1981.

Ro83 Rogers V.C., K. K. Nielson, and G. B. Merrell, The Effects of Advection on Radon-222 Transport Through Earthen Materials, NUREG/CR-3409, Nuclear Regulatory Commission, 1983.

# APPENDIX A

# ESTIMATED POPULATIONS NEAR OPERATIONAL URANIUM ORE PROCESSING SITES

Source: U.S. Environmental Protection Agency, Office of Radiation Programs, Final Environmental Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192), EPA 520/1-83-008-1, Washington, D.C., September 1983

Table 1. Estimated Population Living Near the Tailings Pile at Canon City, Colorado, June 1983
(Latitude 38°23'46"; Longitude 105°13'45")
Total Population (0.0-5.0 km): 5933

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | 5 | 935 | 1158 |
| NNE | - | - | - | 124 | 899 | 715 |
| NE | - | - | - | 39 | 715 | 303 |
| ENE | - | - | - | - | 88 | 52 |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | 5 | - |
| S | - | - | - | - | 3 | 8 |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | 16 | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | 47 |
| NNW | - | - | - | - | 122 | 699 |
| Total | - | - | - | 184 | 2,767 | 2,982 |

- Indicates 0.

Table 2. Estimated Population Living Near the Tailings Pile at
Uravan, Colorado, June 1983
(Latitude 38°22'N.; Longitude 105°45'W.)
Total Population (0.0-5.0 km): 349

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | 45 | 108 | - | - | - |
| NNE | - | 77 | 9 | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | 11 | - | - | - | - |
| E | - | 14 | 28 | - | - | - |
| ESE | - | - | - | 6 | 3 | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | 48 | - | - | - |
| Total | - | 147 | 193 | 6 | 3 | - |

- Indicates 0.

Table 3. Estimated Population Living Near the Tailings Pile at Ambrosia Lake, New Mexico, June 1983
(Latitude 35°23'39"N.; Longitude 107°49'47"W.)
Total Population (0.0-5.0 km): 1

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - |  | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | 1 | - | - |
| Total | - | - | - | 1 | - | - |

- Indicates 0.

Table 4. Estimated Population Living Near the Tailings Pile at Bluewater, New Mexico, June 1983
(Latitude 35°16'12"N.; Longitude 107°56'44"W.)
Total Population (0.0-5.0 km): 907

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | 6 | - |
| SE | - | - | - | 38 | 10 | 13 |
| S | - | - | 6 | 29 | 13 | - |
| SSW | - | - | - | 41 | 13 | 19 |
| SW | - | - | - | 6 | 171 | - |
| WSW | - | - | - | 16 | 418 | - |
| W | - | - | - | 3 | 16 | - |
| WNW | - | - | - | 3 | 19 | 54 |
| NW | - | - | - | - | - | 13 |
| NNW | - | - | - | - | - | - |
| Total | - | - | 6 | 136 | 666 | 99 |

- Indicates 0.

Table 5. **Estimated Population Living Near the Tailings Pile at Church Rock, New Mexico, June 1983 (Latitude 35°38'47"N.; Longitude 108°30'08"W.) Total Population (0.0-5.0 km): 312**

| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| | | | Radial Distance (km) | | | |
| N | - | - | 7 | - | - | - |
| NNE | - | - | - | - | 15 | - |
| NE | - | - | - | - | 19 | - |
| ENE | - | - | - | - | 7 | - |
| E | - | - | - | - | - | 15 |
| ESE | - | - | - | - | 7 | 19 |
| SE | - | - | - | 4 | 11 | 19 |
| SSE | - | - | 7 | 4 | 4 | 22 |
| S | - | - | - | - | - | 41 |
| SSW | - | - | - | 15 | 22 | 19 |
| SW | - | - | - | 4 | - | 15 |
| WSW | - | - | - | 7 | - | - |
| W | - | - | 4 | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | 11 | - | - |
| NNW | - | - | 7 | 7 | - | - |
| Total | - | - | 25 | 52 | 85 | 150 |

- Indicates 0.

Table 6. Estimated Population Living Near the Tailings Pile at Marquez, New Mexico, June 1983
(Latitude 35°18'59"N.; Longitude 107°16'26"W.)
Total Population (0.0-5.0 km): 15

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | 15 | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | 15 | - | - |

- Indicates 0.

## Table 7. Estimated Population Living Near the Tailings Pile at Milan, New Mexico, June 1983
(Latitude 35°14'31"N.; Longitude 107°51'46"W.)
Total Population (0.0-5.0 km): 396

| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| | | | Radial Distance (km) | | | |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | 3 | - |
| ENE | - | - | - | - | - | - |
| E | - | - | 3 | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | 3 | - | - | - |
| S | - | - | 51 | 22 | - | - |
| SSW | - | - | 67 | 16 | 29 | 41 |
| SW | - | - | 44 | 3 | - | 10 |
| WSW | - | - | 22 | 63 | 13 | 6 |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | 190 | 104 | 45 | 57 |

- Indicates 0.

Table 8. Estimated Population Living Near the Tailings Pile at Seboyeta, New Mexico, June 1983
(Latitude 35°11'09"N.; Longitude 107°20'09"W.)
Total Population (0.0-5.0 km): 166

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | 32 | 19 |
| W | - | - | - | - | - | 35 |
| WNW | - | - | - | - | 10 | 70 |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | 42 | 124 |

- Incicates 0.

Table 9. Estimated Population Living Near the Tailings Pile at Edgemont, South Dakota, June 1983
(Latitude 43°17'43"N.; Longitude 103°48'46"W.)
Total Population (0.0-5.0 km): 1,421

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | 5 | 8 | - | - |
| NNE | - | - | 3 | 5 | 8 | 10 |
| NE | - | - | - | 3 | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | 3 | 3 | - |
| SE | - | - | - | - | 3 | - |
| SSE | - | - | - | - | 3 | - |
| S | - | - | - | - | - | 3 |
| SSW | - | - | - | - | - | - |
| SW | - | - | 20 | - | 3 | 5 |
| WSW | 3 | - | 63 | - | - | - |
| W | 18 | 20 | 306 | 58 | - | - |
| WNW | 10 | 18 | 612 | 94 | 8 | - |
| NW | - | - | 83 | - | - | 10 |
| NNW | - | - | 33 | - | - | - |
| Total | 31 | 38 | 1,125 | 171 | 28 | 28 |

- Indicates 0.

Table 10. Estimated Population Living Near the Tailings Pile
at Panna Maria, Texas, June 1983
(Latitude 28°57'33"N.; Longitude 97°56'31"W.)
Total Population (0.0-5.0 km): 453

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | 3 | - | - | 9 |
| NE | - | - | 3 | - | 6 | 3 |
| ENE | - | - | - | 6 | - | 18 |
| E | - | - | 9 | 12 | 21 | 68 |
| ESE | - | - | 9 | 3 | 9 | - |
| SE | - | - | 6 | - | - | 3 |
| SSE | - | 6 | - | - | - | - |
| S | - | 6 | 9 | - | - | 6 |
| SSW | - | - | 3 | - | 6 | 24 |
| SW | - | - | - | - | 3 | 6 |
| WSW | - | - | - | 6 | 12 | 9 |
| W | - | - | - | 3 | 15 | 136 |
| WNW | - | - | - | - | 6 | - |
| NW | - | - | - | 3 | 3 | - |
| NNW | - | - | - | - | - | 3 |
| Total | - | 12 | 42 | 33 | 81 | 285 |

- Indicates 0.

## Table 11. Estimated Population Living Near the Tailings Pile at Falls City, Texas, June 1983
(Latitude 28°54'03"N.; Longitude 98°05'40"W.)
Total Population (0.0-5.0 km): 42

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | 3 | - | 3 |
| NE | - | - | - | 3 | 6 | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | 3 | 3 |
| SSE | - | - | - | - | - | 6 |
| S | - | - | - | - | - | 6 |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | 6 | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | 3 | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | 3 | 12 | 9 | 18 |

- Indicates 0.

Table 12. Estimated Population Living Near the Tailings Pile at Ray Point, Texas, June 1983
(Latitude 28°51'11"N.; Longitude 98°06'05"W.)
Total Population (0.0-5.0 km): 130

| Direction | Radial Distance (km) 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | 3 | 9 | 6 | 14 |
| NE | - | - | 3 | 3 | - | - |
| ENE | - | - | - | 3 | 3 | 3 |
| E | - | - | 6 | 3 | 9 | 6 |
| ESE | - | - | 9 | - | 6 | - |
| SE | - | - | - | - | 3 | - |
| SSE | - | - | - | 3 | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | 3 | 35 |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | 21 | 21 | 30 | 58 |

- Indicates 0.

Table 13. Estimated Population Living Near the Tailings Pile at Blanding, Utah, June 1983
(Latitude 37°31'37"N., Longitude 109°30'33"W.)
Total Population (0.0-5.0 km): 8

| Direction | Radial Distance (km) 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | 4 |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | 4 |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | 8 |

- Indicates 0.

Table 14. Estimated Population Living Near the Tailings Pile at Rio Algom Site, La Sal, Utah,
June 1983
(Latitude 38°16'N.; Longitude 109°16'30"W.)
Total Population (0.0-5.0 km): 343

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | 53 | 85 | 12 | - |
| NNE | - | 8 | 28 | 57 | - | 40 |
| NE | - | - | 4 | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | 4 | - |
| NW | - | - | - | - | - | 4 |
| NNW | - | - | 20 | 12 | 16 | - |
| Total | - | 8 | 105 | 154 | 32 | 44 |

- Indicates 0.

## Table 15. Estimated Population Living Near the Tailings Pile at Moab, Utah, June 1983

(Latitude 38°35'59"N.; Longitude 109°35'44"W.)
Total Population (0.0-5.0 km): 2361

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | 6 | - | - | - |
| E | - | - | 3 | 3 | - | - |
| ESE | - | - | - | 9 | 674 | 668 |
| SE | - | - | - | - | 420 | 557 |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | 21 | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | 9 | 33 | 1094 | 1225 |

- Indicates 0.

### Table 16. Estimated Population Living Near the Tailings Pile at Hanksville, Utah, June 1983

(Latitude 37°43'06"N.; Longitude 110°40'51"W.)

Total Population (0.0-5.0 km): 171

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | 171 |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | 171 |

- Indicates 0.

## Table 17. Estimated Population Living Near the Tailings Pile at Dawn Mill, Ford, Washington, June 1983

(Latitude 47°54'06"N.; Longitude 117°49'58"W.)
Total Population (0.0-5.0 km): 411

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | 20 | 12 | 15 | - |
| NNE | - | - | 20 | 3 | 6 | - |
| NE | - | - | 15 | 12 | 20 | 12 |
| ENE | - | - | 29 | 29 | 6 | - |
| E | - | 3 | - | - | - | - |
| ESE | - | - | - | - | - | 3 |
| SE | - | - | - | - | 3 | 35 |
| SSE | - | - | - | - | - | - |
| S | - | - | - | 3 | 3 | 3 |
| SSW | - | - | - | - | 9 | - |
| SW | - | - | - | - | 3 | 3 |
| WSW | - | - | - | 3 | 15 | - |
| W | - | - | - | 58 | 6 | 3 |
| WNW | - | - | - | 23 | - | - |
| NW | - | - | - | 3 | - | - |
| NNW | - | - | 9 | 12 | - | - |
| Total | - | 3 | 93 | 157 | 96 | 62 |

- Indicates 0.

Table 18. Estimated Population Living Near the Tailings Pile
at Wellpinit, Washington, June 1983
(Latitude 47°52'27"N., Longitude 118°07'00"W.)
Total Population (0.0-5.0 km): 49

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | 3 | 6 |
| SE | - | - | - | - | 3 | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | 3 |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | 3 |
| W | - | - | - | - | 26 | - |
| WNW | - | - | - | - | - | 5 |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | 32 | 17 |

- Indicates 0.

Table 19. Estimated Population Living Near the Tailings Pile at Powder River, Converse County, Wyoming, June 1983
(Latitude 43°05'N.; Longitude 105°30'W.)
Total Population (0.0-5.0 km): 6

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | | |
| NNE | - | - | - | - | 6 | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | | |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | | |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | | |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | 6 | - |

- Indicates 0.

Table 20. Estimated Population Living Near the Tailings Pile at Gas Hills, (Federal American Partners) Fremont County, Wyoming, June 1983 (Latitude 42°47'59"N.; Longitude 107°30'08"W.) Total Population (0.0-5.0 km): 0

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | - |

- Indicates 0.

Table 21. Estimated Population Living Near the Tailings Pile at Red Desert, Sweetwater County, Wyoming, June 1963 (Latitude 42°02'56"N.; Longitude 107°53'28"W.)
Total Population (0.0-5.0 km): 0

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | - |

- Indicates 0.

### Table 22. Estimated Population Living Near the Tailings Pile (Pathfinder Mines) at Gas Hills, Fremont County, Wyoming, June 1983
(Latitude 42°49'55"N., Longitude 107°29'23"W.)
Total Population (0.0-5.0 km): 0

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | 58 | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | 58 | - | - |

- Indicates 0.

Table 23. **Estimated Population Living Near the Tailings Pile (Pathfinder) at Shirley Basin, Carbon County, Wyoming, June 1983**
**(Latitude 42°20'N.; Longitude 106°12'W.)**
**Total Population (0.0-5.0 km): -0**

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | * |
| S | - | - | - | - | * | * |
| SSW | - | - | - | - | * | * |
| SW | - | - | - | - | * | * |
| WSW | - | - | - | - | - | * |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | - |

- Indicates 0.
* Area covered by intersecting Petrotomics Shirley Basin Mill to the South.

Table 24. Estimated Population Living Near the Tailings Pile (Petrotomics) at Shirley Basin, Carbon County, Wyoming, June 1983
(Latitude 42°20'N.; Longitude 106°12'W.)
Total Population (0.0-5.0 km): 357

| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| | Radial Distance (km) | | | | | |
| N | - | - | - | - | * | * |
| NNE | - | - | - | - | * | * |
| NE | - | - | - | - | * | * |
| ENE | - | - | - | - | - | * |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | 178 | - |
| SSW | - | - | - | - | 179 | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | 357 | - |

- Indicates 0.
* Area covered by intersecting Pathfinder Shirley Basin Mill to the North.

Table 25. Estimated Population Living Near the Tailings Pile (Rocky Mountain Energy) at Powder River, Converse County, Wyoming, June 1983
(Latitude 43°16'N.; Longitude 105°37'W.)
Total Population (0.0-5.0 km): 0

| Direction | Radial Distance (km)<br>0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
|---|---|---|---|---|---|---|
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | - |

- Indicates 0.

Table 26. Estimated Population Living Near the Tailings Pile at UCC-Gas Hills, Natrona County, Wyoming, June 1983
(Latitude 42°49'45"N.; Longitude 107°29'34"W.)
Total Population (0.0-5.0 km): 0

| Direction | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | - | - | - | - | - |
| SE | - | - | - | - | - | - |
| SSE | - | - | - | - | - | - |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | - | - |
| WSW | - | - | - | - | - | - |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | - | - | - |
| NNW | - | - | - | - | - | - |
| Total | - | - | - | - | - | - |

- Indicates 0.

Table 27. Estimated Population Living Near the Tailings Pile at Jeffrey City, Fremont County, Wyoming, June 1983
(Latitude 42°30'32"N.; Longitude 107°47'14"W.)
Total Population (0.0-5.0 km): 906

| | Radial Distance (km) | | | | | |
|---|---|---|---|---|---|---|
| Direction | 0.0-0.5 | 0.5-1.0 | 1.0-2.0 | 2.0-3.0 | 3.0-4.0 | 4.0-5.0 |
| N | - | - | - | - | - | - |
| NNE | - | - | - | - | - | - |
| NE | - | - | - | - | - | - |
| ENE | - | - | - | - | - | - |
| E | - | - | - | - | - | - |
| ESE | - | 3 | - | - | - | - |
| SE | - | - | - | 21 | 6 | - |
| SSE | - | - | - | 3 | - | 9 |
| S | - | - | - | - | - | - |
| SSW | - | - | - | - | - | - |
| SW | - | - | - | - | 140 | - |
| WSW | - | - | - | - | 551 | 167 |
| - | | | | | | |
| W | - | - | - | - | - | - |
| WNW | - | - | - | - | - | - |
| NW | - | - | - | 3 | - | - |
| NNW | - | - | - | 3 | - | - |
| Total | - | 3 | - | 30 | 697 | 176 |

- Indicates 0.

# APPENDIX B

## TECHNICAL INFORMATION MEMORANDUM ON RADON EMISSIONS FROM OPERATIONAL URANIUM MILL FACILITIES

Prepared for PEI Associates, Inc.,
by Rogers & Associates Engineering Corp.

February 22, 1985

# 1. INTRODUCTION

PEI Associates, Inc., under contract to the U.S. Environmental Protection Agency, has requested Rogers and Associates Engineering Corporation (RAE) to characterize radon emissions from active uranium mills and mill tailings disposal sites. The specific task is to provide normalized radon emission-rate expressions for the several radon sources on the uranium mill site. The expressions are to be normalized to the Ra-226 or equivalent uranium in the ore materials and tailings. They are also to include considerations of the variability of radon emissions according to uranium ore region. The variability is denoted by average characteristics for each of the specific states in the uranium-milling regions, i.e., Colorado, New Mexico, Utah, Washington, and Wyoming. Some of the parameters causing the variation in the state-averaged radon emissions are radon emanation coefficient and meteorological conditions such as precipitation, ambient temperature and evaporation potential.

Radon releases from thick sources that remain undisturbed for extended periods of time, occur by diffusive and advective mechanisms. Accordingly, the radon emission is characterized by a normalized radon flux expression. Ore storage pads and mill tailings piles are examples of this source-type. Conversely, sources for which the radon release occurs rapidly from a mechanical disturbance, such as the crushing and grinding operation, are best characterized by a radon release per unit mass; e.g., pCi of radon per pound $U_3O_8$ produced by the mill. For the more rapid releases, the radon release rate is also readily associated with the mill capacity and ore grade.

Chapter 2 of this report contains a more detailed description of the radon sources from a uranium milling facility. A discussion of control strategies for the radon sources is given in Chapter 3, and a description of the analysis and calculation methods is given in Chapter 4. A data base and detailed calculations are next presented in Chapter 5. The results and discussion are given in Chapter 6, and a summary is presented in Chapter 7.

# 2. DESCRIPTIONS OF RADON SOURCES

The significant radon sources in the environment of an operating uranium mill include the ore stockpiles, the crushing and extraction operation, and the tailings impoundment. Other sources, such as contaminated former ore storage areas, raffinate ponds, or other contaminated areas, also may be present at certain mills, but are considered to be sufficiently small and of such uncertainty in size, source strength, and frequency of occurence to be neglected from the present analyses. As illustrated by Figure 1, some of the radon sources can be described as discrete, total-release events while others are continual, diffusion-limited releases. The following descriptions characterize the typical parameters and conditions that are generic to these sources.

## 2.1 ORE PILE DESCRIPTION

An operating uranium mill typically has a number of ore stockpiles located on-site. The stockpiles provide a reserve ore supply to keep the mill operating efficiently despite possible irregularities in the ore production rate at the mine. They also serve as a basis for blending ores of varying grades to match the optimum uranium concentrations for which the mill's extraction process was designed. A survey of eight uranium mine/mill facilities in Wyoming(1,2) demonstrated a wide range in the numbers of ore stockpiles, their sizes, and the average residence time of the stockpiled ores. The ore residence times varied from four to 180 days, with a mean and standard deviation of 87±72 days.(2)

Since several different grades and types of ores are typically stockpiled, and since their size is controlled to facilitate handling, the stockpiles are modeled in terms of discrete piles of fixed size. The number of piles is determined by the product of the mill feed rate (tons/day) and the stockpile residence time (days) divided by the mass of a pile (tons). The geometry of the piles varies among different mills, but it is frequently observed to be that of a wedge (Figure 1), with a ramp length of 200 ft., a ramp width of 60 ft., a maximum height of 30 ft., and 45° sloping sides. The individual ore stockpile volumes and surface areas have been estimated to be 8032 $m^3$ and 2456 $m^2$, respectively.(2) The stockpiles are considered to emit radon from an infinitely thick source from all surfaces, even though the front of the wedge is thin. This gives a conservatively high radon estimate for about 10 percent of the pile areas, but is justified by the highly variable sizes, geometries, and other characteristics of the ore stockpiles. As illustrated in Figure 2, the stockpiles initially emit no radon because all of the emanated radon stored in the pores of the ore was released as the ore was removed from the mine and transported to the stockpiles. As new radon is emanated into the pore space of the ore, the interstitial radon levels and also the escaping radon flux increases with the 3.8-day half-life of radon. After several weeks, a nearly constant radon flux is attained.

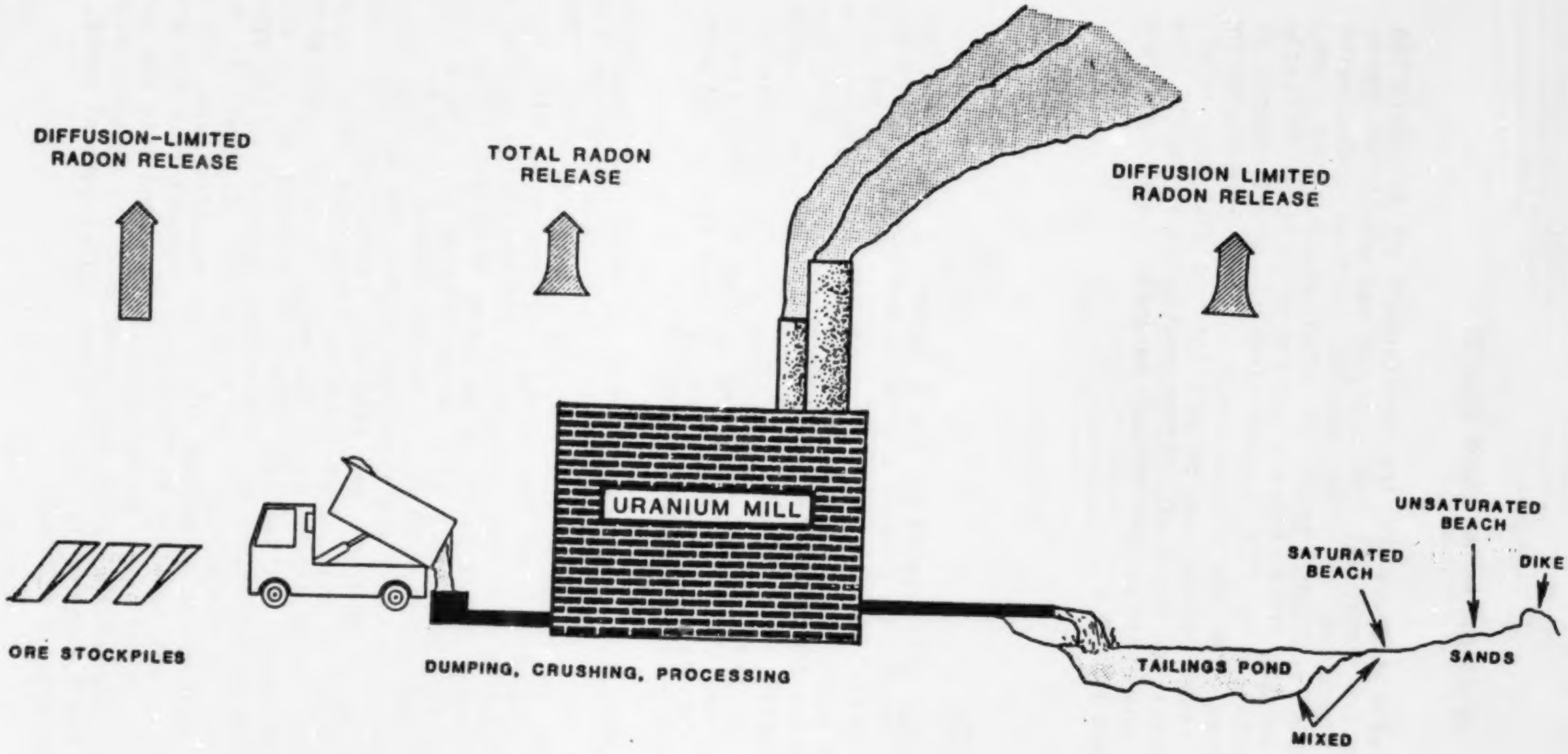
DIFFUSION-LIMITED RADON RELEASE
TOTAL RADON RELEASE
DIFFUSION LIMITED RADON RELEASE
URANIUM MILL
ORE STOCKPILES
DUMPING, CRUSHING, PROCESSING
TAILINGS POND
MIXED
SATURATED BEACH
UNSATURATED BEACH
SANDS
DIKE

Figure 1. Schematic Illustration of the Radon Sources at a Uranium Mill

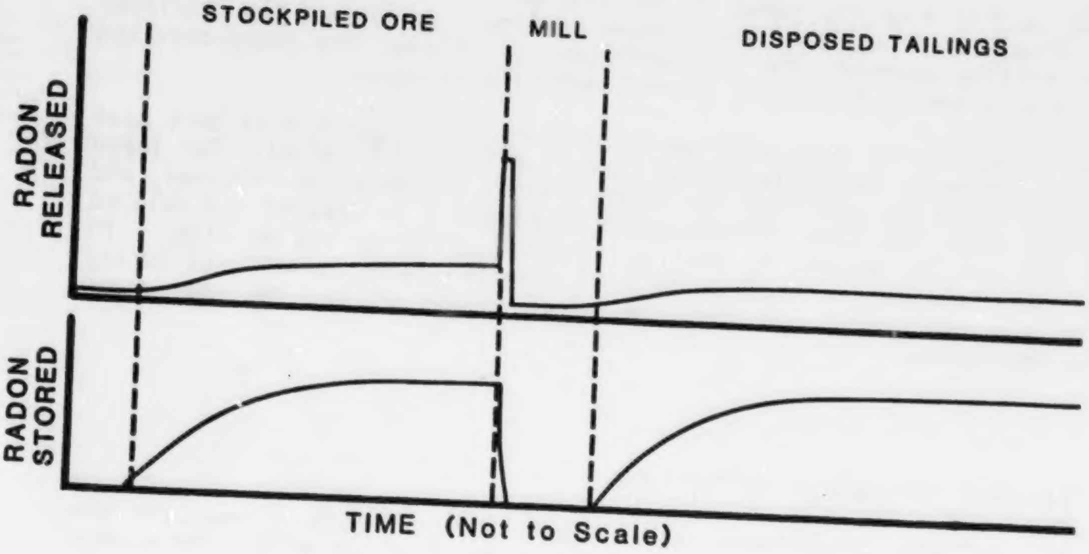

Figure 2. Time Sequence of Gaseous Radon Storage and Release from the Active Uranium Mill.

Although the stockpiles are sorted by ore grade, they are invariably blended to the average or optimum feed grade upon entry to the mill. They are therefore modelled as having identical average radium contents, since both the initial total radon release and the longer-term, diffusion-controlled radon releases all scale linearly with radium content. The radium contents are estimated from ore grades, assuming secular equilibrium between the uranium-238 and the radium-226.

## 2.2 URANIUM MILL DESCRIPTION

The uranium mill, illustrated in Figure 1, utilizes physical and chemical processes to remove uranium from the ore. These can simply be categorized as crushing and grinding to reduce the ore to a small particle size, and leaching and extraction to dissolve and remove the uranium. The remaining leached solids and the liquid wastes are disposed of as a slurry in the tailings impoundment. Due to the finite size of most uranium mills, and their relatively large throughput (thousands of tons per day), the residence time of ore in the mill is less than one day. Hence, the ore does not release large quantities of new radon in the mill circuit unless its previously-emanated radon was not completely released.

The total release of radon from the dumping, crushing and extraction processes occurs mostly during the process of transferring and dumping the ore into the mill feed area (Figure 1). This is because the ore has typically been reduced to sizes of less than 40 cm, the relaxation diameter for ore pieces with diffusion coefficients of $10^{-3}$ $cm^2/s$. Radon thus escapes readily from the pores of the ore when it is handled, causing the total release of accumulated radon shown in Figure 2. During the remainder of the milling process, the ore continues to release the newly-emanated radon, but it has no additional stored radon for release.

An exception to this description is hard-rock uranium ores that have very low diffusion coefficients for radon ($10^{-4}$ to $10^{-5}$ $cm^2/s$). For these ores, four to 14-cm particles can significantly reduce radon releases, and hence the sharp one-time release shown in Figure 2 is reduced and delayed until the ore is ground to smaller particle sizes during milling. In either case, however, a total release of emanated radon is achieved during milling and extraction, so that the exact timing of the release is of little importance.

## 2.3 TAILINGS IMPOUNDMENT DESCRIPTION

The tailings impoundment, also illustrated in Figure 1, receives the mill tailings in a slurry with the liquid wastes from the mill. The slurry pipeline is typically moved to different positions around the edge of the tailings pond so that the sands, which settle most readily, deposit at the outer edges of the pond while the slimes concentrate closer to the center.

In generically describing the tailings impoundment, as illustrated by Figure 1, the unsaturated tailings adjacent to the dikes are considered to be comprised of sands, extending above the water level. The beach areas are considered to be comprised of a 70 percent sand, 30 percent slime mixture that is kept saturated by an identical elevation of water from the tailings pond. The surface beneath the water level is considered to be comprised of 50 percent slimes and 50 percent sands.

As illustrated in Figure 2, tailings initially entering the impoundment are depleted in free, gaseous radon, and hence require several days to contribute to the total radon flux. Since the daily input of new tailings is small compared to the total mass of existing tailings, however, the new additions have no significant impact in lowering the rate of radon release.

## 3. CONTROL STRATEGIES

Very little attention is currently being directed towards control strategies for radon emissions from operating uranium milling facilities. The applicable regulations (40CFR192) provide restrictions on all radionuclide effluents except radon during operations. As a consequence, dust control measures are generally implemented in all aspects of uranium milling and mill tailings containment.

Only two radon control measures have been seriously considered during operations. These are increasing the fraction of the tailings pile under water, and designing the tailings impoundment into a series of smaller cells so that as the individual cells are filled, the surface-to-volume ratio is lower than for one large pile. Furthermore, completed cells after a drying period, can be covered in order to further reduce radon emissions. An additional action that was incorporated into the regulations several years ago involves the use of clean earthen materials for the tailings impoundment dikes instead of tailings sands.

The results of the present study, given in Chapter 6, reveal that radon control strategies for the dry beach tailings areas would be most effective in reducing radon emissions from a uranium milling facility.

# 4. RADON RELEASE CALCULATION METHODS

Quantitative estimates have been made of the radon releases from each of the radon sources described in Chapter 2. These utilized standard radon diffusion and transport equations as described in References 3 and 4, along with newly-measured data on radon transport rates through water. The following paragraphs describe the specific methods used to compute the radon releases from the ore piles, the mill, and from the tailings impoundment.

## 4.1 ORE PILE CALCULATIONS

As shown in Figure 2, the emanated (gaseous) radon is initially depleted at the time the ore is dumped onto the stockpiles. This is a result of the handling and loading operations prior to reaching the stockpiles. The ideal buildup of interstitial radon inside the stockpiles follows the usual exponential approach to equilibrium

$$C = C_{eq}\,(1-e^{-\lambda t}) \qquad (1)$$

where

$C$ = the interstitial radon concentration at a particular time (pCi/l)

$C_{eq}$ = the equilibrium interstitial radon concentration if no releases occurred

$\lambda$ = the radon decay constant (0.181 $d^{-1}$)

$t$ = the elapesed time since dumping of the ore (d)

The radon fluxes released from the surfaces of the ore stockpiles follow an analogous increase to a constant value after initial placement.

Radon fluxes released from the surfaces of the stockpiles are computed using the RAECOM code,(3) or they can be calculated from the equation

$$J_o = 10^4\, R\rho E \sqrt{\lambda D_o}\, \tanh\left(X_o \sqrt{\lambda / D_o}\right) \qquad (2)$$

where

$J_o$ = radon flux from the ore surface (pCi $m^{-2}$ $s^{-1}$)

R = specific activity of radium-226 (pCi/g)

$\rho$ = bulk ore density ($g/cm^3$)

E = radon emanation fraction (dimensionless)

$\lambda$ = radon decay constant ($2.1 \times 10^{-6}$ $s^{-1}$)

$D_o$ = diffusion coefficient for radon in the ore pile ($cm^2/s$)

$X_o$ = thickness of the ore (cm)

Equation 2 is simplified by eliminating the hyperbolic tangent term, since the ore piles constitute an infinitely thick radon source over nearly all of their surfaces. The resulting equation is altered to include the initial time-dependence, and gives

$$J_o = 10^4 R\rho E \sqrt{\lambda D_o} \, (1-e^{-\lambda t}) \qquad (3)$$

In order to compare and evaluate integrated radon releases from different ore grades and regions, Equation 3 is divided by the radium activity, R, and normalized to the average equilibrium emission rate, giving

$$J_o/R = 10^4 \rho E \sqrt{\lambda D_o} \left\{1-[1-\exp(-\lambda T)]/\lambda T\right\} \qquad (4)$$

where

T = ore stockpile residence time (days)

$J_o/R$ = mean radon emission rate (pCi $m^{-2}$ $s^{-1}$ per pCi/g)

Expressing Equation 4 in units of Ci $m^{-2}$ $yr^{-1}$ $\%U_3O_8^{-1}$ gives the analogous equation

$$J_o/G = 887 \rho E \sqrt{\lambda D_o} \left\{1-[1-\exp(-\lambda T)]/\lambda T\right\} \qquad (5)$$

where

G = average ore grade ($\%U_3O_8$)

The total ore stockpile surface area to be used with Equations 4 and 5 in estimating total radon releases is defined as

$$A_s = 0.278\ C_m T/\rho \qquad (6)$$

where

$C_m$ = mill capacity (tons per day)

$A_s$ = total stockpile surface area ($m^2$)

## 4.2 URANIUM MILL CALCULATIONS

The radon releases shown in Figure 2 from the uranium mill occur in two steps. The first is modeled as a complete release of all emanated radon that has been stored in the interstitial spaces of the ore, and the second is the release of all radon that is generated by the ore during its transit through the mill.

The first release is described mathematically for a mill with equilibrated piles ($T \geq 12$ days) as

$$S_1 = 2780\ RE\ C_m \left[X_s + \left(e^{-X_s\sqrt{\lambda/D_o}} - 1\right)/\sqrt{\lambda/D_o}\right] \qquad (7)$$

where

$S_1$ = radon release in moving ore into mill (pCi/day)

$X_s$ = mean thickness of ore stockpiles (cm)

Also, $S_1$ may be expressed as radon released per pound of uranium produced by the mill from the relationship

$$S_2 = \frac{0.05\ S_1}{C_m\ G} = 3.91\text{x}10^5\ E \left[X_s + \left(e^{-X_s\sqrt{\lambda/D_o}} - 1\right)/\sqrt{\lambda/D_o}\right] \qquad (8)$$

where

$S_2$ = pCi radon released per pound of $U_3O_8$ produced by the mill

The second type of radon release in the mill is that of the newly-generated radon that is emanted during the transit time through the mill. This is simply defined as

$$S_3 = RE\ \lambda T_m \qquad (9)$$

where

$T_m$ = mean transit time for ore passing through the mill (sec)

$S_3$ = pCi radon released per gram of ore processed

Expressing Equation 9 in units of pCi radon released per day of mill operation gives

$$S_4 = 9.1\text{x}10^5\ RE\ \lambda T_m\ C_m \qquad (10)$$

where

$S_4$ = pCi Rn/day

and similarly expressing it in units of pCi radon released per pound of $U_3O_8$ produced gives

$$S_5 = 2.32\text{x}10^7\ E\ T_m \qquad (11)$$

where

$S_5$ = pCi Rn/lb $U_3O_8$

## 4.3 IMPOUNDMENT CALCULATIONS FOR UNCOVERED TAILINGS

Radon is released from the uncovered tailings impoundment by diffusion in a manner similar to the release from the ore stockpiles. Since the unsaturated and saturated beach sources of radon are largely unaffected by the continual addition of new tailings, however, the radon release can be considered to be constant, ignoring the depletion of gaseous radon in the newly-deposited tailings. This is particularly true when considering the long-term residence of these materials relative to the half-life of radon (3.8 days).

The radon fluxes from the sandy, unsaturated tailings surfaces and from the saturated beach surfaces can both be described using the one-region, infinite-source equation

$$J_t = 10^4 R\rho E \sqrt{\lambda D_t} \qquad (12)$$

where

$J_t$ = radon flux from the tailings surface (pCi $m^{-2}$ $s^{-1}$)

$D_t$ = radon diffusion coefficient for the tailings ($cm^2/s$)

## 4.4 RADON EMISSIONS FROM TAILINGS PONDS

Radon emissions from the ponded areas of tailings piles have generally been ignored in previous uranium mill tailings studies.(4,5,6) Since radon migration through materials is considered to be dominated by the diffusion mechanism, and since the radon diffusion coefficient for water is so low ($10^{-5}$ $cm^2$ $s^{-1}$), it has been concluded previously that the ponded areas of tailings piles release a negligible amount of radon compared to other radon sources in the uranium milling site. However, the tailings pond is not a totally stagnant body of water. Considerable water movement occurs within the pond over time periods comparable to the half-life of radon. This movement is partly caused by wind currents, thermal gradients, and mechanical disturbance from the mill discharge pipe.

Another source of radon emissions from the tailings pond is the dissolved radium in the acidic water. Water motion also can release a greater fraction of the radon produced from the dissolved radium than the fraction predicted from diffusion theory.

The analysis of radon releases from the tailings pond is divided into the following three components:

1. Radon originating from solid tailings in pond areas less than one meter deep.
2. Radon originating from solid tailings in pond areas greater than one meter deep.
3. Radon from the dissolved radium in the pond water.

Because this subject has not received a comprehensive theoretical treatment to date, the expressions developed herein for radon emissions from the tailings pond are partly based on the experimental measurements given in the Appendix, on engineering judgement, and on extrapolations of diffusion theory parameters and expressions.

### 4.4.1 Shallow Pond Releases

Water movement in the shallow portions of the tailings pond is sufficient to effectively remove radon from the tailings-water interface and transport it to the surface in a relatively short time, resulting in a flux from the surface of the water that is nearly the same as the flux from saturated bare tailings, as given by Equation 12. Water disturbance relaxation lengths from wave action and thermal gradients indicate that a water layer of at least one meter is subject to this motion. Therefore, a pond depth of one meter is selected to define the shallow pond releases.

### 4.4.2 Deep Pond Releases

Water at depth may be less subject to turbulence and motion than the near-surface water. Therefore, the radon transport properties of pond water at depths greater than one meter are modeled with diffusion theory using an effective diffusion coefficient to partially account for the water movement that does occur.(7) The value for this effective diffusion coefficient is obtained from the experimental laboratory measurements of an undisturbed water column over tailings as described in the appendix.

### 4.4.3 Releases From Dissolved Radium

The same water motion that facilitates radon releases from the shallow ponds is also attributed to allowing the release of all the radon generated from dissolved radium in the top meter of the pond. Thus, the applicable flux equation is

$$J_w = 10^6 K_s R\lambda \tag{13}$$

where

$K_s$ = ratio of radium in solution to radium in tailings solids (g/l)

These three sources are combined linearly to obtain a simplified estimate for the average flux from the tailings pond

$$J = 10^4 R\rho E \sqrt{\lambda D_t}\,(f_{sh} - f_{sh}A_t + A_t) + 10^6 K_s R\lambda(1 - 0.5 f_{sh}) \tag{14}$$

where

$f_{sh}$ = fraction of pond less than 1m deep

$A_t$ = attenuation factor for deep water

The attenuation factor, $A_t$, is determined from RAECOM calculations. It can also be approximated by

$$A_t = \exp[-\sqrt{\lambda/D_e}\,(X_p - 100)] \qquad (15)$$

where

$D_e$ = effective stagnant water diffusion coefficient ($cm^2\ s^{-1}$)

$X_p$ = average pond depth for areas greater than 1m deep (cm)

## 5. DATA BASE

In order to estimate the releases of radon from active uranium mills, a variety of site-specific parameters must be defined. Although some of these parameters, such as ore grades, areas of the tailings impoundment surfaces, etc., are readily known or measurable, others, such as the radon diffusion coefficients, radon emanation coefficients, etc., are usually unknown and must be estimated without direct site-specific measurements. The parameters in each of these categories are listed in Table I, along with additional, secondary parameters that are used as a basis for estimating the main parameters of interest.

As indicated in Table I, the basis for several key parameters such as the radon diffusion coefficients for the ores and tailings sands depend on moistures, which are in turn dependent on region-dependent precipitation and evaporation (see Reference 3). For the present analyses, these climatological data were averaged by state for a number of active or recently active mills.

The secondary parameters porosity, moisture content, fractional moisture saturation, and radon diffusion coefficient were calculated from the data base in Table II, and are presented for the ore stockpiles in Table III. Moistures are presented as a range to include varying textures (20 percent to 80 percent passing a #200 mesh), and the mean was used for the diffusion coefficient calculation. Equations used for the porosity, moisture, saturation, and diffusion coefficient calculations are shown in Table I. The radon emission rates computed for the ore stockpiles are also shown in Table III both in terms of the radon flux per unit radium content and in terms of the radon flux per unit ore grade (from Equations 4 and 5). The normalization to unit ore grade assumes equilibrium between the uranium-238 and the radium-226 (2812 pCi/g per percent $U_3O_8$).

Similar calculations were performed for radon emissions from the unsaturated, sandy tailings comprising the outer edges of the tailings impoundment. These are presented in Table IV, and again include the computed parameters porosity, moisture, saturation fraction, and diffusion coefficient for the tailings sands. The computed radon releases utilize Equation 12, with normalizations as in Equations 4 and 5, as for the corresponding columns in Table III. The radon release columns in Table IV are also normalized by the factor 0.54 to account for the typical 4:1 ratio of radium activity in the slimes compared to the sands, and also to account for their bulk density difference as defined in Table I. The resulting data in Table IV are thus normalized to the average radium and equilavent uranium concentrations of the tailings, not that for just the sands alone.

Table V presents the same calculated porosity, moisture, saturation and diffusion coefficient parameters for the mixed tailings comprising the remainder of the beach areas. These are assumed to occur in a 70/30 mass ratio of sands/slimes, and to have a mean combined density of 1.57 g/cm$^3$. As shown in Table V, the mixture is also considered to be saturated. The

## TABLE I

## PARAMETERS USED IN ESTIMATING RADON EMISSIONS FROM ACTIVE URANIUM MILLS

| Parameter | Basis |
|---|---|
| $R_o, R_t$ - Mean radium activity in ore and tailings | Average ore grade for mill $R = 2812\ G$ |
| $G$ - Uranium ore grade (%$U_3O_8$) | Mill records or assumed value |
| $\varrho$ - Bulk density of ore and tailings (g/cm$^3$) | Typical nominal values of 1.7 g/cm$^3$ for ore, 1.6 g/cm$^3$ for sand tailings, and 1.5 g/cm$^3$ for slime tailings |
| $p$ - Porosity of ore and tailings | Computed from $P = 1 - \varrho/g$ |
| $g$ - Specific gravity of ore and tailings (g/cm$^3$) | Data base |
| $D_o, D_t$ - Radon diffusion coefficients for ore and tailings (cm$^2$/s) | Computed as $D = .07 \exp\left[-4(m-mp^2 + m^5)\right]$ |
| $m$ - Moisture saturation fraction | Computed as $m = 10^{-2} M \frac{1}{\varrho} - \frac{1}{g} -1$ |
| $M$ - moisture content (% dry wt) | Computed as $M = 3.1\ P^{1/2} - 0.3E_L + 3.9f_c - 1.0$ |
| $E_L$ - Lake evaporation (inches/yr) | Data base - NOAA |
| $P$ - Precipitation (inches/yr) | Data base - NOAA |
| $f_c$ - Fraction of Solids passing #200 mesh | Typical nominal range of 20% to 80% |
| $X_s$ - Mean thickness of ore stockpiles (cm) | Typical nominal value of 15 ft (457 cm) |
| $T$ - Ore stockpiles residence time (d) | Typical nominal value of 87 days (Reference 2) |
| $\lambda$ - Radon decay constant | $2.1 \times 10^{-6}\ s^{-1}$ or $0.181\ d^{-1}$ |
| $E$ - Radon emanation coefficient | Data base |
| $C_m$ - Mill throughput capacity (tons/d) | Data base |
| $T_m$ - Ore transit time through mill (d) | Typical nominal value of 1d |
| $X_w$ - Mean thickness of tailings pond water (cm) | Typical nominal value of 100 cm |
| $D_w$ - Radon transport coefficient for water (cm$^2$/s) | Empirical data - Appendix |

## TABLE II

## DATA BASE VALUES USED IN ESTIMATING STATE AVERAGE AND SECONDARY PARAMETER VALUES

|  | Mill | Location | State | Precip. (in/yr) | Lake Evap. (in/yr) | Specific Gravity $(g/cm^3)$ | Radon Emanation Fraction, E | Mill Capacity (tons/day) |
|---|---|---|---|---|---|---|---|---|
| 1 | Exxon Highland | N. of Glenrock | WY | 12 | 43 | 2.62 | 0.51 | 3200 |
| 2 | Pathfinder Lucky Mac | Gas Hills | WY | 11 | 42 | 2.62 | .15 | 2500 |
| 3 | Petrotomics | Shirley Basin | WY | 12 | 43 | 2.65 | .20 | 1500 |
| 4 | Pathfinder Sh. Bas. | Shirley Basin | WY | 12 | 43 | 2.65 | .20 | 1800 |
| 5 | Union Carbide | Gas Hills | WY | 11 | 42 | 2.65 | .20 | 1400 |
| 6 | Bear Creek | N. of Glenrock | WY | 12 | 43 | 2.65 | .20 | 2000 |
| 7 | Minerals Exploration | Red Desert | WY | 8 | 39 | 2.65 | .20 |  |
| 8 | Western Nuclear | Jeffrey City | WY | 12 | 42 | 2.63 | .16 | 1700 |
|  | MEAN |  | WY | 11 | 42 | 2.64 | .23 |  |
| 9 | Atlas Minerals | Moab | UT | 8 | 41 | 2.72 | .13 | 1400 |
| 10 | Rio Algom | La Salle | UT | 18 | 40 | 2.65 | .17 | 750 |
| 11 | White Mesa | Blanding | UT | 16 | 45 | 2.65 | .20 | 2000 |
| 12 | Plateau Resources | Ticaboo | UT | 10 | 47 | 2.65 | .20 |  |
|  | MEAN |  | UT | 13 | 43 | 2.67 | .18 |  |
| 13 | Anaconda | Grants | NM | 12 | 56 | 2.54 | .45 | 6000 |
| 14 | Homestake | Grants | NM | 12 | 56 | 2.58 | .39 | 3400 |
| 15 | Kerr-McGee | Grants | NM | 12 | 56 | 2.65 | .39 | 7000 |
|  | MEAN |  | NM | 12 | 56 | 2.59 | .41 |  |
| 16 | Cotter | Canon City | CO | 12 | 45 | 3.10 | .22 | 1200 |
| 17 | Union Carbide | Uravan | CO | 16 | 38 | 2.68 | .22 | 1300 |
|  | MEAN |  | CO | 14 | 41 | 2.89 | .22 |  |
| 18 | Dawn | Ford | WA | 20 | 40 | 2.65 | .20 | 450 |
| 19 | West. Nucl. Sherwood | Wellpinit | WA | 20 | 40 | 2.65 | .20 | 2000 |
|  | MEAN |  | WA | 20 | 40 | 2.65 | .20 |  |
| 20 | Chevron | Hobson | TX | 30 | 56 | 2.65 | .20 | 2500 |

## TABLE III

## SECONDARY PARAMETERS AND RADON EMISSION RATES COMPUTED FOR ORE STOCKPILES

| Mill | Ore Porosity | Moisture (dry wt %) | Saturation of Ore (fraction) | $D_o$ ($cm^2/s$) | $J_o/R$ ($pCi\ m^{-2}s^{-1}/pCi/g$) | $J_c/G$ ($Ci\ m^{-2}y^{-1}/\%\ U_3O_8$) |
|---|---|---|---|---|---|---|
| 1 | 0.35 | 9.2 - 11.6 | 0.51 | 0.010 | 1.18 | 0.104 |
| 2 | .35 | 8.8 - 11.1 | .48 | .012 | 0.38 | .034 |
| 3 | .36 | 9.2 - 11.6 | .49 | .011 | .48 | .043 |
| 4 | .36 | 9.2 - 11.6 | .49 | .011 | .48 | .043 |
| 5 | .36 | 8.8 - 11.1 | .47 | .012 | .51 | .045 |
| 6 | .36 | 9.2 - 11.6 | .49 | .011 | .48 | .043 |
| 7 | .36 | 7.4 - 9.7 | .40 | .017 | .60 | .053 |
| 8 | .35 | 9.3 - 11.6 | .51 | .010 | .37 | .033 |
| MEAN WY | | | | | 0.56±.26 | 0.050±.023 |
| 9 | .37 | 7.3 - 9.7 | .39 | .018 | .40 | .036 |
| 10 | .36 | 11.7 - 14.1 | .61 | .0060 | .30 | .027 |
| 11 | .36 | 10.8 - 13.2 | .57 | .0076 | .40 | .036 |
| 12 | .36 | 8.2 - 10.5 | .44 | .014 | .55 | .048 |
| MEAN UT | | | | | 0.41±.10 | 0.037±.009 |
| 13 | .33 | 8.8 - 11.2 | .52 | .0094 | 1.01 | .089 |
| 14 | .34 | 8.8 - 11.2 | .50 | .011 | .94 | .084 |
| 15 | .36 | 8.8 - 11.2 | .47 | .012 | .99 | .087 |
| MEAN NM | | | | | 0.98±.04 | 0.087±.003 |
| 16 | .45 | 9.2 - 11.5 | .39 | .019 | .70 | .062 |
| 17 | .37 | 11.0 - 13.4 | .56 | .0081 | .46 | .041 |
| MEAN CO | | | | | 0.58±.17 | 0.052±.015 |
| 18 | .36 | 12.4 - 14.8 | .64 | .0049 | .32 | .029 |
| 19 | .36 | 12.4 - 14.8 | .64 | .0049 | .32 | .029 |
| MEAN WA | | | | | 0.32 | 0.029 |
| 20 | .36 | 15.1 - 17.4 | .77 | .0016 | .18 | .016 |
| MEAN TX | | | | | 0.18 | 0.016 |

## TABLE IV

## SECONDARY PARAMETERS AND RADON EMISSION RATES COMPUTED FOR UNSATURATED SANDY TAILINGS

| Mill | Tailings Porosity | Moisture (dry wt %) | Tailings Saturation (fraction) | $D_t$ ($cm^2/s$) | $J_t/R$ ($pCi\ m^{-2}s^{-1}/pCi/g$) | $J_t/G$ ($Ci\ m^{-2}y^{-1}/\%\ U_3O_8$) |
|---|---|---|---|---|---|---|
| 1 | 0.39 | 8.4 | 0.35 | 0.021 | 0.92 | 0.082 |
| 2 | .39 | 8.0 | .33 | .023 | .29 | .025 |
| 3 | .40 | 8.4 | .34 | .022 | .37 | .033 |
| 4 | .40 | 8.4 | .34 | .022 | .37 | .033 |
| 5 | .40 | 8.0 | .32 | .024 | .39 | .035 |
| 6 | .40 | 8.4 | .34 | .022 | .37 | .033 |
| 7 | .40 | 6.6 | .26 | .029 | .43 | .038 |
| 8 | .38 | 8.5 | .36 | .020 | .28 | .025 |
| MEAN WY | | | | | 0.43±.20 | 0.038±.018 |
| 9 | .41 | 6.5 | .26 | .029 | .28 | .025 |
| 10 | .40 | 11.0 | .44 | .015 | .26 | .023 |
| 11 | .40 | 10.0 | .40 | .018 | .33 | .030 |
| 12 | .40 | 7.4 | .30 | .025 | .39 | .035 |
| MEAN UT | | | | | 0.29±.04 | 0.028±.005 |
| 13 | .37 | 8.0 | .35 | .020 | .80 | .071 |
| 14 | .38 | 8.0 | .34 | .021 | .71 | .063 |
| 15 | .40 | 8.0 | .32 | .024 | .76 | .067 |
| MEAN NM | | | | | 0.76±.05 | 0.067±.004 |
| 16 | .48 | 8.4 | .28 | .029 | .47 | .042 |
| 17 | .40 | 10.3 | .41 | .017 | .36 | .032 |
| MEAN CO | | | | | 0.42±.08 | 0.037±.007 |
| 18 | .40 | 11.7 | .47 | .013 | .29 | .025 |
| 19 | .40 | 11.7 | .47 | .013 | .29 | .025 |
| MEAN WA | | | | | 0.29 | 0.025 |
| 20 | .40 | 14.3 | .57 | .0081 | .23 | .020 |
| MEAN TX | | | | | 0.23 | 0.020 |

## TABLE V

## SECONDARY PARAMETERS AND RADON EMISSION RATES COMPUTED FOR MIXED SATURATED BEACH TAILINGS

| Mill | Tailings Porosity | Moisture (dry wt %) | Tailings Saturation (fraction) | $D_t$ ($cm^2/s$) | $J_t/R$ ($pCi\ m^{-2}s^{-1}/pCi\ g^{-1}$) | $J_t/G$ ($Ci\ m^{-2}y^{-1}/\%\ U_3O_8$) |
|---|---|---|---|---|---|---|
| 1 | 0.40 | 25.5 | 1.0 | $4.5\times10^{-5}$ | 0.078 | 0.0069 |
| 2 | .40 | 25.5 | 1.0 | $4.5\times10^{-5}$ | .023 | .0020 |
| 3 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 4 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 5 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 6 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 7 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 8 | .40 | 25.5 | 1.0 | $4.5\times10^{-5}$ | .024 | .0022 |
| MEAN WY | | | | | 0.035±.018 | 0.0031±.0016 |
| 9 | .42 | 26.8 | 1.0 | $4.8\times10^{-5}$ | .020 | .0018 |
| 10 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .026 | .0023 |
| 11 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 12 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| MEAN UT | | | | | 0.027±.005 | 0.0024±.0004 |
| 13 | .38 | 24.2 | 1.0 | $4.2\times10^{-5}$ | .067 | .0059 |
| 14 | .39 | 24.8 | 1.0 | $4.3\times10^{-5}$ | .058 | .0052 |
| 15 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .060 | .0053 |
| MEAN NM | | | | | 0.062±.005 | 0.0055±.0004 |
| 16 | .49 | 31.2 | 1.0 | $6.1\times10^{-5}$ | .039 | .0035 |
| 17 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .034 | .0030 |
| MEAN CO | | | | | 0.036±.004 | 0.0032±.0004 |
| 18 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| 19 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| MEAN WA | | | | | 0.031 | 0.0027 |
| 20 | .41 | 26.1 | 1.0 | $4.6\times10^{-5}$ | .031 | .0027 |
| MEAN TX | | | | | 0.031 | 0.0027 |

resulting radon fluxes normalized to both the average radium content and to the average original ore grade (percent $U_3O_8$) are tabulated and averaged by state.

For the ponded areas of the tailings, it is assumed that half the tailings under the pond are slimes and half are sands. It is also assumed that approximately one-fourth of the pond area is less than one meter deep. Other key parameters not quantified previously include $K_s$ and the diffusion coefficients for saturated tailings and stagnant water.

The value of $K_s$, obtained from Reference 4, is $8.92 \times 10^{-4}$ g/ml. It is used for the analysis of all sites, because appropriate site specific values were not available.

The diffusion coefficient for saturated tailings was deduced from laboratory measurements described in the Appendix. The derived value was within the experimental uncertainty of the value obtained from the correlation given in Table I; therefore, the correlation value of about $4 \times 10^{-5}$ cm$^2$ s$^{-1}$ was used in the calculations.

A lower-bound estimate of the diffusion coefficient for the deep water was obtained from laboratory measurements of D for a 19 cm stagnant water column over 9 cm of tailings. A value of 0.003 cm$^2$ s$^{-1}$ was obtained with the effective D of the stagnant column. This was used in RAECOM calculations for representative field conditions to obtain an average attenuation factor of 0.17, which was used for $A_t$ in the analysis.

Table VI contains the normalized flux values using the above data values in Equation 14.

Table VII presents the radon releases computed for the handling of ore in the mill yard and for the releases during milling. These releases are based respectively on calculations from Equations 8 and 11, and are given in units of pCi of radon released per pound of $U_3O_8$ produced. Similar results can also be tabulated from Equations 7 and 10 in units of pCi/day of radon release if the ore grade or radium content is known, and using the mill capacities (tons/day) listed in Table II. The equivalent results in Table VII can also be readily converted to pCi/day releases of radon by multiplying by the ore grade and mill capacity as

$$\text{pCi/day} = \underset{\text{(release)}}{\frac{\text{pCi}}{\text{lb } U_3O_8}} \cdot \underset{\text{(grade)}}{\frac{\%\ U_3O_8}{100}} \cdot \underset{\text{(mill capacity)}}{\frac{2000 \text{ lb}}{\text{ton ore}} \cdot \frac{\text{tons ore}}{\text{day}}} \qquad (16)$$

## TABLE VI

## SECONDARY PARAMETERS AND RADON EMISSION RATES COMPUTED FOR TAILINGS SLIMES

| Mill | $J_t/R$ (pCi $m^{-2}s^{-1}$/pCi $g^{-1}$) | $J_t/G$ (Ci $m^{-2}y^{-1}$/% $U_3O_8$) |
|---|---|---|
| 1 | 0.041 | 0.0036 |
| 2 | .015 | .0014 |
| 3 | .019 | .0017 |
| 4 | .019 | .0017 |
| 5 | .019 | .0017 |
| 6 | .019 | .0017 |
| 7 | .019 | .0017 |
| 8 | .016 | .0014 |
| MEAN WY | 0.021±.008 | 0.0019±.0007 |
| 9 | .014 | .0012 |
| 10 | .017 | .0015 |
| 11 | .019 | .0017 |
| 12 | .019 | .0017 |
| MEAN UT | 0.017±.002 | 0.0015±.0002 |
| 13 | .036 | .0032 |
| 14 | .032 | .0029 |
| 15 | .032 | .0029 |
| MEAN NM | 0.033±.002 | 0.0030±.0002 |
| 16 | .020 | .0018 |
| 17 | .020 | .0018 |
| MEAN CO | 0.020 | 0.0018 |
| 18 | .019 | .0017 |
| 19 | .019 | .0017 |
| MEAN WA | 0.019 | 0.0017 |
| 20 | .019 | .0017 |
| MEAN TX | 0.019 | 0.0017 |

## TABLE VII

## RADON RELEASES FROM HANDLING AND MILLING OF URANIUM ORES

| Mill | Handling Release (pCi/lb $U_3O_8$) | Milling Release (pCi/lb $U_3O_8$) |
|---|---|---|
| 1 | $7.7x10^7$ | $1.2x10^7$ |
| 2 | $2.2x10^7$ | $3.5x10^6$ |
| 3 | $3.0x10^7$ | $4.6x10^6$ |
| 4 | $3.0x10^7$ | $4.6x10^6$ |
| 5 | $3.0x10^7$ | $4.6x10^6$ |
| 6 | $3.0x10^7$ | $4.6x10^6$ |
| 7 | $2.9x10^7$ | $4.6x10^6$ |
| 8 | $2.4x10^7$ | $3.7x10^6$ |
| MEAN WY | $3.4x10^7$ | $5.3x10^6$ |
| 9 | $1.9x10^7$ | $3.0x10^6$ |
| 10 | $2.7x10^7$ | $3.9x10^6$ |
| 11 | $3.1x10^7$ | $4.6x10^6$ |
| 12 | $2.9x10^7$ | $4.6x10^6$ |
| MEAN UT | $2.6x10^7$ | $4.0x10^6$ |
| 13 | $6.9x10^7$ | $1.0x10^7$ |
| 14 | $5.9x10^7$ | $9.0x10^6$ |
| 15 | $5.8x10^7$ | $9.0x10^6$ |
| MEAN NM | $6.2x10^7$ | $9.3x10^6$ |
| 16 | $3.1x10^7$ | $5.1x10^6$ |
| 17 | $3.4x10^7$ | $5.1x10^6$ |
| MEAN CO | $3.2x10^7$ | $5.1x10^6$ |
| 18 | $3.2x10^7$ | $4.6x10^6$ |
| 19 | $3.2x10^7$ | $4.6x10^6$ |
| MEAN WA | $3.2x10^7$ | $4.6x10^6$ |
| 20 | $3.4x10^7$ | $4.6x10^6$ |
| MEAN TX | $3.4x10^7$ | $4.6x10^6$ |

## 6. RESULTS AND DISCUSSION OF RADON EMISSIONS

The results of the data base calculations of radon emission rates are summarized by state in Table VIII. These emission rates form the basis for generic evaluations of total radon releases from active uranium mills, and they are also compared with field measurements for the few cases in which empirical data are available.

### 6.1 TOTAL RADON EMISSIONS FROM EMISSION RATE DATA

In order to assess the relative importance of the six radon source components listed in Table VIII, an example calculation of total radon emissions is presented here. This example also serves to illustrate the detailed application of the emission rate data. In the following example, a uranium mill in Wyoming is defined to have a capacity of 1500 tons/day, with an average ore grade of 0.1 percent $U_3O_8$. It is also defined to have the average ore stockpile residence time of 87 days, and to have nominal densities and other parameters as defined in Table I. The total area of the ore stockpiles is computed from Equation 6 to be 121,340 $m^2$. Radon release rates for the ore stockpiles are thus computed to be

$$(0.56)(21340\ m^2)(86400\ s/d)(281.2\ pCi/g)(10^{-12}\ Ci/pCi) = 0.290\ Ci/d$$

For ore handling, the radon release rate is

$$(3.4E7)(2000\ lb/ton)(0.001\ lb\ U_3O_8/lb\ ore)(1500\ tons/d)(10^{-12}\ Ci/pCi) = 0.102\ Ci/d$$

For ore milling, the radon release rate is

$$(5.3E6)(2000\ lb/ton)(0.001\ lb\ U_3O_8/lb\ ore)(1500\ ton/d)(10^{-12}\ Ci/pCi) = 0.016\ Ci/d$$

Assuming $9x10^4$ $m^2$ of unsaturated sandy beach area, the release rate is

$$(0.43)(9.0E4\ m^2)(86400\ s/d)(281.2\ pCi/g)(10^{-12}\ Ci/pCi) = 0.940\ Ci/d$$

Assuming $2x10^5$ $m^2$ of saturated beach area, the release rate is

## TABLE VIII

## SUMMARY OF RADON EMISSION RATES BY STATE

| Radon Source | State |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  | CO | NM | TX | UT | WA | WY | Mean |
| Ore Stockpiles ($pCi\ m^{-2}s^{-1}/pCi\ g^{-1}$) | 0.58 | 0.98 | 0.18 | 0.41 | 0.32 | 0.56 | 0.51 |
| Ore Handling ($pCi/lb\ U_3O_8$) | 3.2E7 | 6.2E7 | 3.4E7 | 2.6E7 | 3.2E7 | 3.4E7 | 3.7E7 |
| Ore Milling ($pCi/lb\ U_3O_8$) | 5.1E6 | 9.3E6 | 4.6E6 | 4.0E6 | 4.6E6 | 5.3E6 | 5.5E6 |
| Unsaturated Tailings ($pCi\ m^{-2}s^{-1}/pCi\ g^{-1}$) | 0.42 | 0.76 | 0.23 | 0.29 | 0.29 | 0.43 | 0.40 |
| Saturated Tailings ($pCi\ m^{-2}s^{-1}/pCi\ g^{-1}$) | 0.036 | 0.062 | 0.031 | 0.027 | 0.031 | 0.035 | 0.037 |
| Tailings Pond ($pCi\ m^{-2}s^{-1}/pCi\ g^{-1}$) | 0.020 | 0.033 | 0.019 | 0.017 | 0.019 | 0.021 | 0.022 |

$$(0.035)(2.0E5\ m^2)(86400\ s/d)(281.2\ pCi/g)(10^{-12}\ Ci/pCi) = 0.170\ Ci/d$$

Assuming $4x10^5$ $m^2$ of pond area, the pond release rate is

$$(0.021)(4.0E5\ m^2)(86400\ s/d)(281.2\ pCi/g)(10^{-12}\ Ci/pCi) = 0.204\ Ci/d$$

The total radon release rate is summed from the above six components to be 1.72 Ci/day.

Similar calculations were performed for the same example uranium mill if located in each of the other states, and the results of these radon release calculations are also presented in Table IX. As indicated, total radon releases vary from about 1.2 to 3.0 Ci/day, and they are dominated by the radon emissions from the sandy, unsaturated edges of the impoundment, which account for about 53 percent of the total. The ore stockpiles and the water-covered tailings pond are next in importance, comprising about 16 percent and 13 percent, respectively, of the total release.

Although some variation is noted in Table IX between the different states, this table represents only the interstate variations that result from changing emanation coefficients, specific gravities, and moisture-related effects on the radon diffusion coefficients. It does not account for the larger effects that result, for example, from the higher evaporation and resulting smaller fraction of water-covered tailings in New Mexico compared to Wyoming or other cooler climates. These parameters can be addressed using site-specific data on water-covered areas with the emission rates in Table VIII.

## 6.2 COMPARISONS WITH PREVIOUS ESTIMATES

The dominant radon emission parameters are estimated to be the radon flux from the unsaturated sand portions of the tailings beaches and the flux from the ore stockpiles. These estimates are both based on the emission rate parameters (specific fluxes) in Table VIII, which can be compared with a limited body of previous data. The mean specific flux from the unsaturated tailings sands was 0.4 pCi $m^{-2}$ $s^{-1}$/pCi $g^{-1}$ (range of 0.23 to 0.76), and that from the ore stockpiles was 0.51 pCi $m^{-2}$ $s^{-1}$/pCi $g^{-1}$ (range of 0.18 to 0.98).

An often-accepted nominal value for specific radon fluxes in unsaturated earthen materials has been 1 pCi $m^{-2}$ $s^{-1}$/pCi $g^{-1}$.(4,8) A set of measured values is presented in Table X. As indicated, the referenced specific fluxes also varied widely (0.22 to 2.2) but they tend to encompass the present range of predicted values for unsaturated ores and tailings.

## TABLE IX

## SUMMARY OF TOTAL RADON EMISSIONS FOR THE EXAMPLE MILL IN VARIOUS STATES (Ci/day)

| Radon Source | State | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | CO | NM | TX | UT | WA | WY | |
| Ore Stockpiles | 0.301 | 0.508 | 0.093 | 0.213 | 0.166 | 0.290 | 0.26 |
| Ore Handling | .096 | .186 | .102 | .078 | .096 | .102 | 0.11 |
| Ore Milling | .015 | .028 | .014 | .012 | .014 | .016 | 0.016 |
| Unsaturated Tailings | .918 | 1.662 | .503 | .634 | .634 | .940 | 0.88 |
| Saturated Tailings | .175 | .301 | .151 | .131 | .151 | .170 | 0.18 |
| Tailings Pond | .194 | .321 | .185 | .165 | .185 | .204 | 0.21 |
| TOTAL | 1.70 | 3.01 | 1.05 | 1.23 | 1.25 | 1.72 | 1.66 |

# TABLE X

# MEAN SPECIFIC RADON FLUXES MEASURED ON VARIOUS SURFACES

| Surface | Mean Specific Radon Flux (pCi $m^{-2}s^{-1}$/pCi $g^{-1}$) | No. of Measurements | Reference |
|---|---|---|---|
| Soil | 0.89 | -- | 9 |
| Soil | 0.85 | -- | 10 |
| Soil | 0.22 | -- | 11 |
| Undisturbed Topsoil | 0.68 | 7 | 2 |
| Overburden Piles | 0.89 | 161 | 2 |
| Ore Stockpiles | 2.20 | 75 | 2 |
| Low-Grade Ore Piles | 1.92 | 80 | 2 |
| Tailings Piles | 0.36 | -- | 12 |
| Tailings Piles | 1.17 | -- | 13 |
| Phosphogypsum Tailings - FL | 0.95 | 141 | 14 |
| Undisturbed Soil - FL | 0.44 | 17 | 15 |
| Sand Mine Tailings - FL | 0.23 | 19 | 15 |
| Phosphate Overburden - FL | 0.28 | 27 | 15 |

The slightly higher specific fluxes quoted for the ore piles in Table X (2.2 and 1.9) are nearly all measured at a single mill site, and thus may not be as representative of a regional average as the collective set of data in Table X.

The most dramatic departure from previous estimates and theoretical evaluations is the observed radon penetration of the tailings pond water. As evidenced by the specific fluxes in Table VIII, the water in the tailings pond has relatively little effect when comparing with the bare, saturated tailings surfaces, even when the 50/50 sand/slime ratio under water is accounted for (70/30 sand/slime ratio used for saturated tailings beaches). The tailings pond water exhibits a much larger transport coefficient than the $10^{-5}$ $cm^2/s$ previously reported,(16) probably due to turbulence and advective currents. Further research to quantify and characterize this transport in a tailings pond is definitely indicated.

# APPENDIX

## LABORATORY MEASUREMENTS OF RADON OVER WATER

Slime tailings from the Rifle, CO, UMTRAP site were oven-dried and 200 g each were measured into four Boyoucos soil test cylinders, designated A, B, C, and D. Seven hundred ml of tap water were added to each cylinder. After allowing equilibrium conditions to occur, a series of measurements were initiated to measure the radon flux from the water after being undisturbed and after fresh air was circulated over the undisturbed water surface. Fluxes were also measured over the bare, saturated tailings from which the overlying water was removed after 550 hours of contact. The geometry of the experimental configuration is shown in Figure A-1. Key parameter values are as follows:

| | |
|---|---|
| Ra-226 in tailings | 4628 pCi/g |
| Radon Emanation Coefficient | 0.25 |
| Tailings Total Porosity | 0.66 |
| Dissolved Ra-226 in separated water | 35 pCi/l |

Radon fluxes were measured by both the accumulator can and charcoal canister techniques.(17) The accumulator can measurements give a ten-minute average flux and the charcoal canister measurements give a 24-hr average flux. The radon fluxes are given in Table A-I. These values are arithmetic averages of several replicate measurements.

RAECOM calculations were used to interpret the flux data. For example, a RAECOM calculation of the saturated bare tailings gave a flux of 83 pCi $m^{-2}$ $s^{-1}$, using the correlation (default value) for D. This compares well with the measured flux value and also supports the selection of $4 \times 10^{-5}$ $cm^2$ $s^{-1}$ for the D of saturated tailings. RAECOM calculations were also used to verify the 17 percent attenuation provided by the undisturbed water over the tailings. An effective diffusion coefficient of 0.003 $cm^2$ $s^{-1}$ was deduced for the undisturbed water.

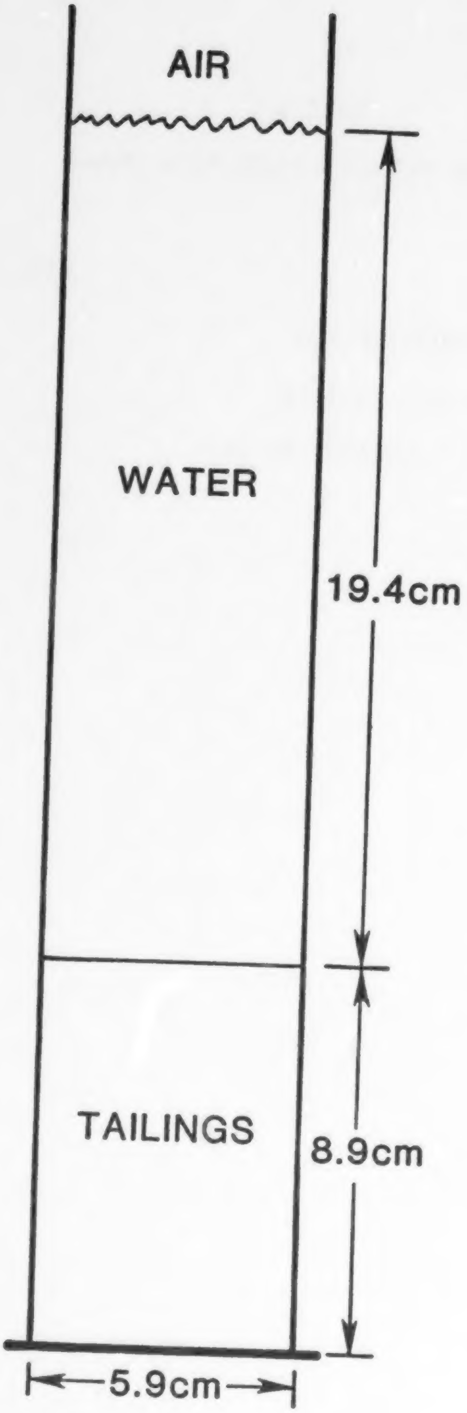
AIR
WATER
19.4cm
TAILINGS
8.9cm
5.9cm

Figure A-1. Geometry of Laboratory Measurements of Radon over Water.

## TABLE A-I

## AVERAGE MEASURED RADON FLUX VALUES

| Test Description | Average[a] Flux (pCi $m^{-2}s^{-1}$) |
|---|---|
| Undisturbed Water - Accumulator Can | 75±19 |
| Undisturbed Water - Charcoal Canister | 68±7 |
| Bare Saturated Tailings - Accumulator Can | 84±21 |

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[a] Mean ± S.D.

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